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Master Thesis

Artificial release of wet snow avalanches

Survey, interviews and case study

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Deklaration

Hiermit versichere ich, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und ich mich auch sonst keiner unerlaubten Hilfe bedient habe. Alle Stellen der Arbeit, die wörtlich oder sinngemäß aus anderen Quellen übernommen wurden, sind als solche kenntlich gemacht. Weiters versichere ich, dass diese Arbeit in gleicher oder ähnlicher Form bisher noch keiner Prüfungsbehörde vorgelegt wurde.

Höchst, 04.05.2014

Martin Oberhammer

Abstract

Negative impact of snow avalanches on infrastructure and human beings can be prevented by different types of avalanche mitigation measures. Short-term mitigation measures are relatively cheap, but long closure times of roads, highways, cableways or ski slopes might result. To reduce closure times, artificial avalanche release is frequently applied in ski areas and above highways and roads. Studies and guidelines on artificial avalanche release are mainly focusing on dry snow avalanches whereas wet snow avalanches have so far got relatively little attention.

As a lot of energy is dissipated in wet snow, artificial release of wet snow avalanches has long been considered as not feasible. Nevertheless, in recent years, avalanche control services have increasingly released wet snow avalanches by explosives. However, it is presently unclear when and under which conditions wet snow avalanche release by explosives is feasible. The objective of this study is, therefore, to collect experience and knowledge of practitioners and to find key factors.

Avalanche control services in Austria, Switzerland and South Tyrol (Italy) were approached with a questionnaire on artificial release of wet snow avalanches to assess the current state. Experienced avalanche professionals were chosen for expert interviews to find out details about timing of control operations and effectiveness of different release methods. To find out more about forecasting of wet snow avalanche activity, a dataset of weather, snowpack and avalanche data was investigated in a case study.

Controlling wet snow avalanches is now common practice in the Austrian and Swiss Alps. Artificial release of wet snow avalanches is feasible and helps to reduce closure times significantly in many areas. Forecasting of wet snow avalanche activity is difficult. Most experts decide whether or not to start a control operation only a few hours before. Timing of control operations is crucial for release success. Wet loose snow avalanches are more frequently triggered than wet slab avalanches. The expected avalanche type depends on snowpack properties. The effectiveness of different release methods has been investigated for wet loose and wet slab avalanches. Compared to dry snow conditions, the effective range of explosives is considerably reduced in wet snow conditions. Thus, more charges are needed. Systematic triggering of wet snow avalanches in order to enforce spreading, snow entrainment and secondary releases can help to empty a starting zone efficiently.

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List of Abbreviations

ADS	avalanche diagnose system
AFADE	avalanche forecasting and diagnose system
AG	Aktiengesellschaft (stock company)
AWS	automatic weather station
CL	cloudiness
CT	column test
DD	wind direction
E	east
EAWS	European avalanche warning services
ECT	extended column test
FF	wind velocity
FFmax	wind maximum velocity
FMCW	frequency modulated continuous wave
HS	snow height
HN	new snow
ICSI	International Commission on Snow and Ice of the International Association of Hydrological Science
IFKIS	Interkantonales Frühwarn- und Kriseninformationssystem für Naturgefahren
IPS	isothermal portion of the snowpack
ISWR	incoming shortwave radiation
kgf	kilogram-force
LWC	liquid water content (volume wetness)
LWDKIP	Lawinenwarndienste Kommunikations- und Informationsplattform
M/F, MF	melt freeze
N	north
n.a.	no answer
NP	non persistent grains
NXD	nearest neighbours program
PD	penetration depth
PST	propagation saw test
P24	day with control operation and precipitation within the last 24h
P72	day with control operation and precipitation within the last 72h
PFP	day with control operation during a precipitation-free period
PG	persistent grains
P*xx*G	day with good release success
P*xx*N	day with no or moderate release success
P*xx*P	previous day
RB	Rutschblock test
RH	relative humidity
S	south
SFT	shear frame test
SMP	snow micro-penetrometer
SL	snow line
SLF	WSL Institut für Schnee- und Lawinenforschung SLF
SP	snow profile
SPP	snow profile program
ST	shovel shear test
TA	air temperature
TBT	tilt board test
TNT	Trinitrotoluene
TRD	Alp Trida
TSS	snowpack surface temperature
TS0	bottom snowpack temperature
Ts25	snowpack temperature 25cm
Ts50	snowpack temperature 50cm
Ts75	snowpack temperature 75cm
W	west
WG	wet grains
WIFI	Wirtschaftsförderungsinstitut
WSL	Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL

1 Introduction

1.1 Problem statement and research objectives

The International Avalanche Classification (ICSI, 1981) differentiates between wet, dry and mixed snow avalanches. 'A wet snow avalanche implies the presence of liquid water throughout the avalanching layer, otherwise the avalanche is dry or mixed.'

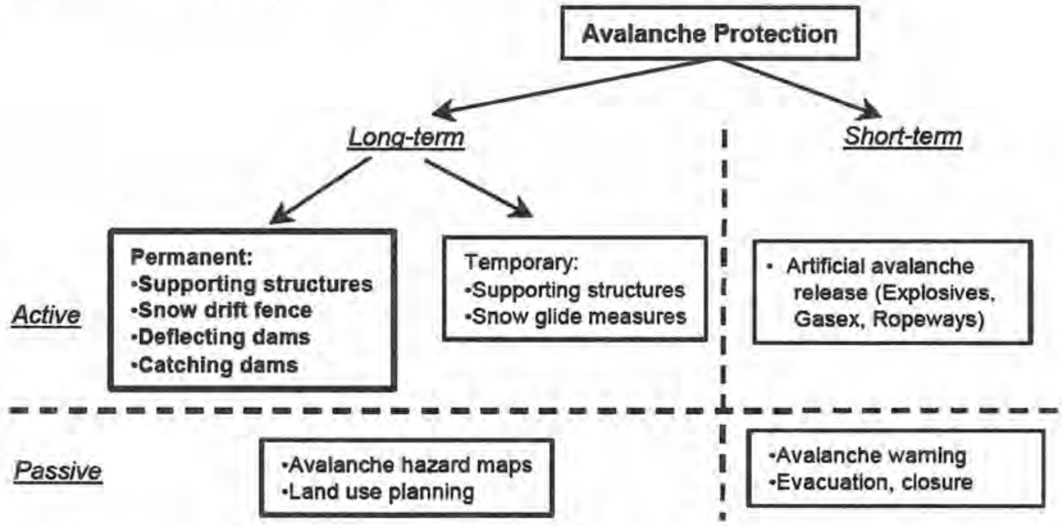
Depending on the snow climate, the importance of wet snow avalanches and their triggers vary significantly. Three major climate types are generally differentiated based on metereological parameters: maritime, transitional and continental snow climates (McCLUNG and SCHAERER, 2006). 'In maritime snow climates or areas of warm snowpacks [...] a large proportion of wet snow avalanches occurs during winter, as a result of wet snowfall, rain and midwinter snowmelt. In continental snow climates or areas of cold snowpacks wet snow avalanches occur almost exclusively in spring. The warm snowpacks tend to be relatively stable in spring during active melt' (KATTELMANN, 1984).

Even if wet snow avalanches cause considerably less damage than dry snow avalanches, the risk and damage potential of wet snow avalanches is not negligible. 'Compared to dry snow avalanches, the flow speed of wet snow avalanches is usually slower and, therefore, the runout distance is usually shorter. However, the impact on obstacles is considerable due to the higher density of wet snow' (EAWS, 2009). According to an analysis of all avalanches causing damages in Switzerland in the period between 1980/81 and 2003/04, wet snow avalanches mainly affect alpine pass roads and ski slopes. About 11% of the avalanche victims have been killed in wet snow avalanches (ZWEIFEL, 2004). Hence, wet snow avalanches are a major concern especially for ski areas, highways, alpine pass roads and backcountry skiers.

Negative impact of snow avalanches on infrastructure and human beings can be prevented by either active or passive avalanche protection measures. Figure 1 gives an overview of different avalanche protection measures: Active measures with long-term effect include protection structures in the strating zones (MARGRETH 2007), tracks or runout zones, whereas artificial avalanche release has only a short-term effect. Passive methods regulate the presence of persons in the danger area (MARGRETH and

BURKARD, 2010). In addition to the measures showed in figure 1, afforestation and forest maintenance in the starting zone complete the options of avalanche protection measures (SAUERMOSER, 2006). The approach of integral avalanche protection combines different measures.

Figure 1: Overview of avalanche protection



Source: MARGRETH and BURKARD, 2010.

The different avalanche protection measures vary significantly in costs and effectiveness. 'Active long-term avalanche control structures should be applied where the damaging potential is big and cheaper control methods, such as evacuation or explosive control, are not easy to apply. These measures are more expensive than short-term or passive measures, but their main advantage is that they are very effective and that a daily hazard evaluation is usually not necessary anymore' (MARGRETH and BURKARD, 2010).

The protection goal, the available budget and legal regulations define the framework to choose protection measures within the design process of an avalanche safety concept for public or private infrastructure. Depending on the protection goal and the available budget, the appropriate protection measures can be figured out by performing a cost effectiveness analysis (WILHELM et al., 2000; WILHELM, 1999) for different approaches on a risk concept basis (BORTER, 1999). 'The outset risk without safety measures, the residual risk and the expected risk reduction are calculated. By comparing the costs and the expected risk reduction, it is possible to compare the different control measures'

(MARGRETH and BURKARD, 2010). Depending on the size of the project, further interests have to be considered in the decision process - for example social, ecological and environmental interests. Therefore, more complex decision support instruments like the cost-benefit analysis (WECK-HANNEMANN and THÖNI, 2006) or the multi criteria analysis (GAMPER et al., 2006) have been introduced to bring transparency, equity and efficiency into the decision making process.

In alpine regions highways and pass roads are often endangered by many avalanche paths (MARGRETH et al., 2003). Depending on the number, size and frequency of the avalanches and on the relevance of the road within the traffic network, it is often the most efficient way to use short-term mitigation measures. These measures are relatively cheap, but long closure times might result. With artificial avalanche release closure times of roads can be reduced (KOGELNIG et al., 2012). Thus, artificial avalanche release is an attractive alternative to active long-term avalanche mitigation structures especially in the context of an integral avalanche mitigation concept.

Although artificial avalanche release is used in many countries as a protection measure for road sections, it is not completely established in all alpine countries. For example, in Italy it is not easy to apply explosives because of strict legal regulations for storing and use of explosives. In Austria only a few roads and highways (HÖLLER, 2007) use artificial avalanche release, but it seems to become more important because of its cost efficiency compared to active long-term mitigation measures (LAND TIROL, 2012).

In ski areas artificial avalanche release has long been used to control avalanches. Artificial release of avalanches is the most efficient mitigation measure to reduce closure times of cableways and ski slopes because of avalanche danger. However, there has been a long discussion in Austria about residual risk and about the possibilites and limits of using artificial avalanche release, but throughout the latest change of the legal framework artificial avalanche release has gained importance with regard to the design of avalanche safety concepts for new cableways (ZECHNER, 2011).

Artificial avalanche release becomes more and more important specially with regard to the release of dry snow avalanches. Studies and guidelines on artificial avalanche release are mainly focusing on dry snow avalanches, whereas wet snow avalanches have so far got relatively little attention.

As a lot of energy is dissipated in wet snow, artificial release of wet snow avalanches has been considered as not feasible (SCHWEIZER, 2007; STOFFEL, 2001). 'The physical properties of the wet snow suppress the propagation of the shock wave essential to the release of a snow slab' (ARMSTRONG, 1976). Nevertheless, in recent years, avalanche control services have increasingly released wet snow avalanches by explosives (SCHWEIZER, 2007; MARIENTHAL et al., 2012; STOFFEL, 2013). However, it is presently unclear when and under which conditions wet snow avalanche release by explosives is feasible. The objective of this study is, therefore, to collect experience and knowledge of practitioners and to find key factors.

Research objectives:

Assess the current state of artificial release of wet snow avalanches in ski areas and above highways / roads.

Determine typical weather patterns causing wet snow instabilities and leading to control operations for wet snow avalanches. Specify the timing for control operations.

Evaluate the effectiveness of different release methods with regard to different types of wet snow avalanches.

Analyse if artificial release is an appropriate mitigation measure for wet snow avalanches and determine the limitations.

The study is mainly focusing on Austria and Switzerland. In these countries artificial avalanche release by explosives above settlements is only an exception (STOFFEL and MARGRETH, 2009) and, therefore, not processed in this study. The study only examines the artificial avalanche release in ski areas and above roads / highways.

The research design of this study combines qualitative and quantitative research methods (MAYRING, 2001): Based on theoretical concepts, a questionnaire-based survey is conducted. The survey provides statistical data on the one hand and collects experience and knowledge of practitioners on the other hand. Collected experience and knowledge is specified and generalised through following-up expert interviews and through a statistical analysis of a dataset of artificially released avalanches.

1.2 Contents and structure

Chapter 1 gives an overview of the problem statement and defines the research objectives.

Chapters 2 and 3 introduce the theoretical concepts covering the topics 'wet snow avalanches' and 'artificial avalanche release'.

Each of the chapters 4, 5 and 6 is structured with an introduction including the definition of the research questions or research hypotheses, a methodology part, a presentation of the results and a final discussion of the results. The results and the conclusions, resulting from the discussion, are incorporated into the research questions or research hypotheses of the following chapter.

Chapter 4 presents the survey on avalanche control services with regard to their experience with artificial release of wet snow avalanches.

Chapter 5 presents the expert interviews with avalanche professionals, performing artificial release of wet snow avalanches, chosen by the best practice principle.

In chapter 6 data of avalanche control operations in the ski area of Ischgl (Austria) is analysed in order to find weather and snowpack parameters to forecast wet snow avalanche activity and to study the effectiveness of different release methods.

The final chapter (7) puts the results from the individual chapters into context and relates them to the research objectives. Finally, topics for further research are suggested.

The appendices A to C provide supplementary information to the chapters 4 to 6.

2 Wet Snow Avalanches

2.1 Classification

The International Avalanche Classification (ICSI, 1981) differentiates between wet, dry and mixed snow avalanches. 'A wet snow avalanche implies the presence of liquid water throughout the avalanching layer, otherwise the avalanche is dry or mixed' (ICSI, 1981). Mixed snow avalanches either have moist or wet snow layers within the starting zone, but the failure plane is still dry (example given in CONWAY and RAYMOND, 1993) - or they start as dry snow avalanches and entrain moist or wet snow in the avalanche path (example given in STUDEREGGER et al., 2010).

The focus of the present study is only on wet snow avalanches. They occur in two distinct morphologies: loose snow and slab avalanches (ICSI, 1981). Loose snow avalanches are characterized by the point fracture mechanism (ICSI, 1981). They 'spread out as they move down the slope in a triangular pattern as more snow is pushed down the slope and entrained into the slide' (MCCLUNG and SCHAERER, 2006). Slab avalanches are starting from a line: They initiate 'by a failure associated with a weak layer at depth in the snow cover, ultimately resulting in a block of snow, usually approximating a rectangular shape, that is entirely cut out by propagating fractures in the snow' (MCCLUNG and SCHAERER, 2006). Depending on the snow properties, the ICSI (1981) differentiates between soft and hard slabs. The fracture mechanism of glide snow avalanches differs from the mechanism of slab avalanches. Therefore, it is occasionally seen as a separate fracture mechanism (NAIRZ, 2010). Glide snow avalanches are not investigated in the present study.

Depending on the position of the sliding surface, avalanches are classified into surface layer and full depth avalanches (ICSI, 1981). While surface layer avalanches release on a weak layer within the snowpack, full depth avalanches release at the bottom (layer) of the snowpack.

Avalanches can release naturally or with human influence. Human released avalanches can either be accidentally or intentionally (artificially) triggered (ICSI, 1981).

2.2 Effect of water on snow

2.2.1 Snow metamorphism

According to the meteorological conditions during snowfall, precipitation particles do have different crystal forms. A classification for newly fallen snow crystals is provided by the ICSI (1981). 'Once deposited, snow crystals begin to change form immediately' caused by physical processes (McClung and Schaerer, 2006). Temperature (gradients) and overburden pressure are main drivers for snow metamorphism. In cold snowpacks with temperatures below 0°C dry snow metamorphism changes precipitation particles into other crystal forms. The rate of crystal change and growth is mainly related to vapor diffusion controlled by the temperature gradient within the snowpack, the pore space size and the geometry (McClung and Schaerer, 2006). Low growth rates produce rounded forms, at the other extreme high growth rates result in faceted or depth hoar crystals (kinetic growth). According to Jamieson (1995), weak layers in dry snowpacks can be classified as either persistent forms or non persistent forms. Non persistent weak layers are generally related to new snow layers in the upper snowpack. Persistent forms usually persist for long periods within the snowpack and include buried surface hoar, facets, depth hoar or crusts (Jamieson, 1995). Due to their persistence over long periods they may be relevant for wet snow instabilities especially during the first wetting of a snowpack.

As soon as the snowpack becomes isothermal and snow gets moist, wet snow metamorphism leads to a growth in grain size and reconfiguration of bonds (McClung and Schaerer, 2006). Depending on the size and form (curvature), snow crystals do have slightly different melting points. 'These small temperature differences cause melting of the smallest grains and most convex surfaces. This leads to grain coarsing and rounding' (Techel, 2010). The rate of growth depends on the water regime of the snowpack. In snow with low water content grain growth occurs by vapor flux through pores caused by vapor pressure differences among different crystal sizes (McClung and Schaerer, 2006). Growth rate increases with increased water content (Brun, 1989). In a water saturated snow grain growth is caused by the heat flux through the water: 'Since small particles have a lower melting temperature than large ones, the small particles melt first. The heat of melting comes from the larger particles, which undergo surface refreezing' (McCLUNG and SCHAERER, 2006). The rate of growth decreases with the increasing size of particles (MARSH, 1991). Wet snow metamorphism leads to wet grains (melt forms) with different subclasses of crystals (ICSI, 1981) like, for example, clustered rounded grains (associated with low water content), melt-freeze polycrystals or slush.

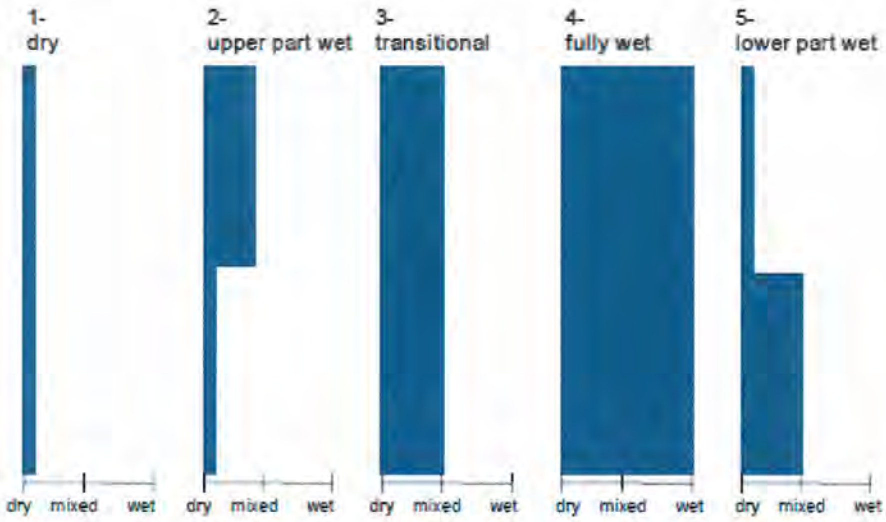
2.2.2 Liquid water content in snowpacks

Snow is kind of a porous medium composed of ice particles (snow crystals) and air in the pore system in between. With the introduction of water at the melting point snow becomes a three-phase-system, where physical and mechanical snow properties can alter rapidly depending on small differences in liquid water content (TECHEL, 2008). With regard to snow characteristics, the liquid water content (LWC) is generally given in volume wetness (vol. %).

Liquid water content in snow can be measured either by destructive or non destructive methods (TECHEL, 2008). The disturbance of the snowpack may influence texture and moisture of the snowpack rapidly. Non destructive measurement devices are placed before snowfall or wetting occurs. Upward looking ground penetrating radar (HEILIG et al., 2009) and snowpack analyser (SOMMER and FIEL, 2010) are tools that can measure liquid water content without disturbance of the snowpack. Destructive methods include centrifugal, calorimetry and dilution devices (TECHEL, 2008). Most commonly dielectric methods like the snow fork (SIHVOLA and TIURI, 1986) and the denoth meter (DENOTH, 1994) are used.

Measurement devices are mainly used for scientific purposes. Many avalanche forecasters and avalanche control services generally estimate water content quantitatively in a snow profile according to the international classification of seasonal snow on the ground (FIERZ et al., 2009) that differentiates between dry, moist (<3% LWC), wet (3-8% LWC), very wet (8-15% LWC) or slush (>15% LWC) snowpack layers. However, several studies (TECHEL and PIELMEIER 2011; FIERZ and FÖHN, 1994) have shown that these estimations poorly correlate with measured LWC especially with increasing water content (TECHEL and PIELMEIER, 2011). Because of uncertainties of estimations and rapid change of LWC in the snowpack, TECHEL and PIELMEIER (2011) propose a more practical classification focusing on a general spatial wetness distribution. The five wetness profile types are shown in figure 2.

Figure 2: Wetness classification of snowpacks



Wetness classification according to the moisture content of the snowpack. Liquid water is introduced by rain or melt (2), into an initially dry snowpack (1). Depending on layering properties, continued water input leads to preferential and lateral water flow and results in different wetting stages of snowpack layers (3). Continued water infiltration and wet snow metamorphism is resulting in a homogeneous fully-wet snowpack (4). A special case is the refreezing of the snowpack or new snow on a moist/wet snowpack (5). Diurnal changes usually occur within the upper snowpack layer (10-15cm) and are not considered in this classification scheme. Source: TECHEL and PIELMEIER, 2011.

Depending on the water content, several classes of water regimes can be differentiated: 'the pendular regime with two different sub-zones, the funicular regime, a pendular-funicular transition zone and the regime of complete saturation' (DENOTH, 2002). The pendular regime includes moist snow with a liquid water content up to about 8% (DENOTH, 1999). Continuous air is present in the pore system between the snow grains. In moist snow water is held by capillary forces and surface tension (DENOTH, 2002) that inhibits drainage - water content is consistent with the irreducible water saturation (DENOTH, 2002). If the water content increases to a value greater than about 4%, gravitational forces exceed and water can freely drain through the pore system (DENOTH, 2002). When the liquid water content exceeds a value of about 8%, isolated water bodies begin to merge and build up continuous liquid paths (transition zone). The transition to the funicular regime takes place in a range between about 11% and 15% (DENOTH, 2003; KATTELMANN, 1984). The funicular regime is characterized by water present in continuous liquid phases within the pore system in combination with a more or less isolated gaseous phase (DENOTH, 1998). In complete saturated snow the pore system is completely filled with liquid water.

2.2.3 Water flow within the snowpack

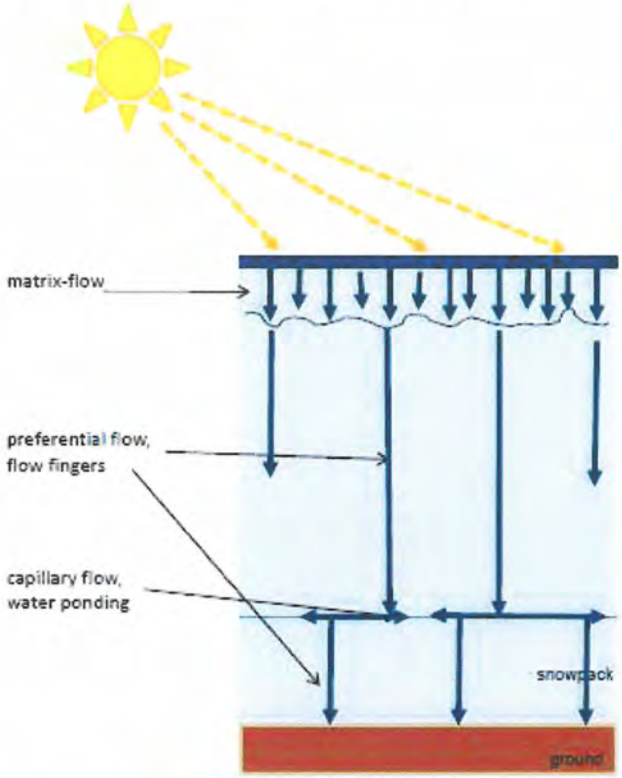
The flow pattern of water in a snowpack depends on the porosity and permeability of snowpack layers (TECHEL, 2010) and the snowpack stratigraphy. Porosity and permeability of snow mainly depend on snow texture, density and grain size. Coarse grained snow is more permeable than fine grained old dry snow (TECHEL, 2010). 'At low water content (pendular regime), the pathways of water within the snow matrix are disconnected and capillary forces are dominant' (MITTERER, 2012). When the liquid water exceeds the irreducible water saturation, water will start to connect and vertical water flow is induced by gravitational forces (TECHEL et al., 2008).

The vertical water flow regime in partially saturated snow is either a matrix flow regime or a preferential flow regime (figure 3). In the matrix flow regime water enters equally into a homogeneous, non-changing snowpack and results in a uniform wetting front. Textural and stratigraphical inhomogeneities - even if there are only small variations - influence permeability, hydraulic conductivity and capillary pressure and, thus, may lead to a formation of flow paths (flow fingers). 'These channels become the preferred pathways for additional water flow as grain size and permeability increase, thus developing a positive feedback meachnism' (KATTELMANN, 1984). Through the preferential flow paths water infiltrates faster and deeper into the snowpack than through homogeneous wetting (TECHEL, 2010). During infiltration through flow fingers, the surrounding snowpack layer can even remain dry (TECHEL, 2010), thus, slab-like characteristics can be retained (PEITZSCH, 2009). BROWN (2008) observed uniform matrix wetting in mature snowpacks. TECHEL (2010) observed matrix flow mainly in layers consisting of persistent grain forms. Preferential wetting was frequently observed in layered ripening snowpacks (BROWN, 2008) - mainly in non persistent layers (TECHEL, 2010). Lateral slope parallel flow often induced preferential wetting in underlying layers (BROWN, 2008; TECHEL, 2010). However, factors leading to preferential flow are presently unclear: PEITZSCH (2009) could not find any 'significant relationship between the amount of water necessary to form flow fingers and snow grain size, snow density, hand hardness, snow temperature or grain type.'

Lateral water flow is induced by capillary barriers or impermeable layers (hydraulic barriers) on inclined terrain (FIERZ und FÖHN, 1994). CONWAY and BENEDICT (1992) observed lateral water flow more often in heterogeneous snow consisting of ice crusts and fine grained layers than in homogeneous stratigraphies with coarse rounded snow. Buried melt-freeze, rain, sun or wind crusts act as hydraulic conductivity boundary (PEITZSCH, 2009). At major textural discontinuities significant capillary pressure gradients act as capillary barrier interface between snow layers (KATTELMANN, 1984). A capillary barrier is built by a layer with fine grained snow with smaller pores above a layer with coarse grained snow (KATTELMANN, 1984). PEITZSCH (2009) investigated snow stratigraphies and layering forming capillary barriers with the introduction of liquid water on dry snowpacks: Grain sizes were observed significantly smaller in the layer above than in the layer below, but 'no significant difference in grain sizes existed between layers above and layers below transition that did not impede water' (PEITZSCH, 2009). The capillary pressure gradient impedes vertical water flow until a pressure equilibrium is established (TECHEL et al., 2008). Coarse grained snow over fine grained snow has no or little impedance on water flow (TECHEL, 2010) and may even accelerate water flow in the upper layer (KATTELMANN, 1984). Lateral water flow often induces finger flow after the break through into the underlying snowpack layer (TECHEL et al., 2008).

The amount of liquid water and snow temperature also influence flow pattern and timing of water infiltration. 'The wetter a draining porous medium, the higher the hydraulic conductivity' (TECHEL, 2010). Infiltration rates are higher in the funicular regime with continuous pore water. Flow fingers can develop much faster in fully isothermal snowpacks than in subfreezing snow (KATTELMANN, 1984). Wet snow metamorphism changes snowpack (layer) characteristics through the infiltration of water, thus, flow patterns also change. 'If wet grain metamorphism is more advanced, higher water flow rates are possible' (TECHEL, 2010). The drainage capacity of a snowpack increases with the proceeding state of wet snow metamorphism and the formation of flow channels or flow fingers.

Figure 3: Flow patterns in a layered snowpack



Source: TECHEL, 2010.

Figure 4: Flow patterns of water in snow tracked by dye tracers

(A) Matrix flow in a mature uniform snowpack. (B) Preferential flow and lateral flow in a moist ripening snowpack. Source: BROWN, 2008.

Flow patterns of water in snow can be investigated by using dye tracers (figure 4) or high frequency FMCW radar (MITTERER, 2012; WIESINGER et al., 2013). Water output at the base of the snowpack can be measured by using a lysimeter (MITTERER, 2012; PEITZSCH et al., 2012).

2.2.4 Physical and mechanical properties of wet snow

Physical and mechanical properties of dry snow change with the introduction of liquid water. Wet snow metamorphism causes structural changes. MARSHALL et al. (1998) observed rapid densification and settlement in combination with the first wetting of low density snow. The rate of densification decreases as density increases (MARSHALL et al., 1998). Snow density measurements in wet snow (TECHEL, 2010) showed a positive correlation between water content and density for non persistent grains but not for persistent grains. Grain rearrangement and densification with the introduction of water cause increased creep velocities (MCCLUNG and SCHAERER, 2006). Wetting at the bottom of snowpacks reduces friction at the snow-ground interface and leads to increased glide velocities (MCCLUNG and SCHAERER, 2006) especially on smooth ground surfaces.

In general, the mechanical strength of a snowpack (layer) decreases as liquid water content increases: 'In the presence of water snow has fewer small grains, fewer points of contact, fewer bonds, and relatively low strength at these bonds' (KATTELMANN, 1984). Snow hardness and shear strength are commonly investigated indicators for the mechanical strength of snowpack layers.

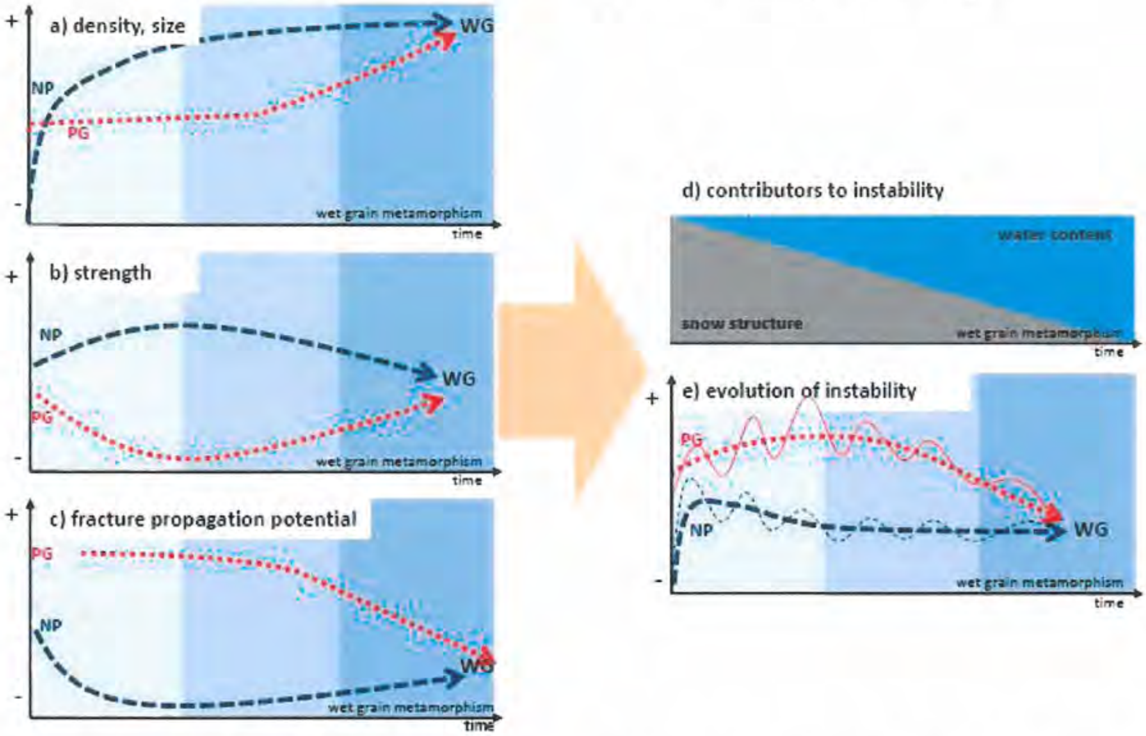
BRUN and REY (1987) and BHUTIYANI (1994) observed only little changes in shear strength below a water content of 6% by volume, but once water content exceeds 6% shear strength decreased significantly by a factor of two (BHUTIYANI, 1994). ZWIMPFER et al. (2012) observed similar behaviour of wetted natural snow during loading experiments under laboratory conditions. According to YAMANOI and ENDO (2002), shear strength decrease can be described as an exponential function of volumetric water content. Melt-freeze grains differentially respond to liquid water addition with regard of shear strength (PERLA et al., 1982). TRAUTMAN et al. (2006) measured surficial shear strength with a shear frame and micro-structural hardness with a snow micro-penetrometer during a melt-freeze cycle. Results suggest a linear correlation between micro-structural hardness and shear strength of snow.

It was generally expected that a major decrease of strength occurs at the transition from the pendular to the funicular water regime (KATTELMANN, 1984; COLBECK, 1982).

Within the funicular water regime wet snow metamorphism accelerates and rapid grain growth results in large grains with reduced bonding and reduced strength (KATTELMANN, 1984). According to IZUMI and AKITAYA (1985), snow hardness decreases exponentially with increasing liquid water content. If water flowing downslope over a layer interface (FIERZ and FÖHN, 1994; CONWAY et al., 1988), 'additional force may be imposed upon the overlying slab' (KATTELMANN, 1984). AMBACH and HOWORKA (1965) and KATTELMANN (1987) observed increased wet snow avalanche activity if the volumetric water content exceeds 7% by volume.

At low water content of less than 3% by volume strength is similar or even larger than dry snow strength because of capillary forces (BRUN and REY, 1987) and induced clustering (MCCLUNG and SCHAERER, 2006). Field experiments of TECHEL (2008, 2010) showed a slight increase in micro-structural penetration resistance and hardness in fine grained non persistent layers with a liquid water content below 3% by volume. However, the penetration resistance decreased for coarse, persistent grains within the same water regime: 'Weak persistent layers undergoing first wetting (or repeated wetting when the faceted grain shape is still well developed) do not require much liquid water to become very weak' (TECHEL, 2010). CONWAY et al. (1988) observed that 'many avalanches of new snow occured well before the moisture content reached 7% by volume.' MITTERER (2012) suggests that for weak layers a small increase in liquid water content results in unstable conditions, but water has to be concentrated in stable snowpacks in order to develop an instability. TECHEL (2010) assumes that 'the strength of snow undergoing first wetting may depend more on dry snow structure (grain shape, size, density) than on the actual liquid water content.' CONWAY (1988) summarizes that the loss of strength with the introduction of water into a layer depends on the structure and type of snow: 'The final crystal type tends toward large rounded grains; the greater the change in crystal shape necessary to achieve this final state, the more quickly the snow became unstable with the introduction of water.' Based on field experiments, TECHEL (2010) suggests a conceptual model (figure 5) of wet snow metamorphism and its impact on strength.

Figure 5: Conceptual model of wet snow metamorphism and its impact on strength



Conceptual model of wet snow metamorphism (WG, wet grains) and 'its impact on strength (fracture initiation) and fracture propagation potential for an isothermal weakness (PG, grain shapes such as facets or depth hoar) and non-persistent weakness (NP, such as precipitation particles or small round grains).' Source: TECHEL, 2010.

The model differentiates between persistent grain shapes (PG, facets or depth hoar) and non persistent grain shapes (NP, precipitation particles or small round grains). The model of TECHEL (2010) suggests that 'initial stability conditions depend mostly on snow structure, while final conditions are mostly driven by liquid water content.' According to the model (figure 5), the fracture propagation potential generally decreases with additional liquid water, but also depends on the grain form combination across the failure plane (TECHEL, 2010). ZWIMPFER et al. (2012) analysed fracture initiation of wetted snow (LWC ~ 6%) in laboratory conditions using a particle image velocimetry. Results showed that 'wet snow allowed much more deformation before failure and rather collapsed than fractured with a recognizable pattern compared to dry snow' (ZWIMPFER et al., 2012).

2.3 Formation mechanism of wet snow avalanches

2.3.1 Wet slab avalanches

According to KATTELMANN (1984), the primary difference between dry and wet slab avalanches is that 'dry snow usually fails due to an increase in shear stress while wet slides usually occur because of a decrease in shear strength.'

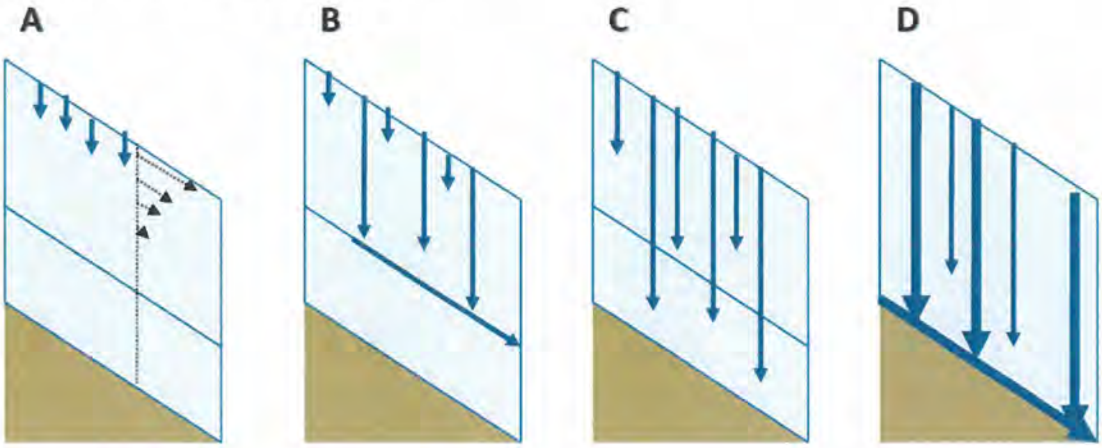
REARDON and LUNDY (2004) mention that the drainage capacity of a snowpack plays a decisive role: 'Wet snow avalanches seem to occur when liquid water production overwhelms the drainage capacity of the snowpack. That can occur in two ways: (1) When there are no preferential flow paths, as when melt (or rain) first introduces liquid water into a cold, dry snowpack, or (2) when flow channels exist but are not sufficient to drain an increase in water volume, such as that produced by increased melting or rain.' 'The structure of the snowpack clearly influences the infiltration of water into the snow' (FIERZ and FÖHN, 1994). Based on observations, TECHEL (2007) proposed that the timing of failures differs depending on snowpack properties: 'An unstable snowpack will avalanche during infiltration, while a stable snowpack only once water lubricates the ground-snow interface.' ARMSTRONG (1976) also mentions snowpack properties as reason for wet slab avalanches by comparing snowpack layering in different wet snow avalanche cycles. BAGGI and SCHWEIZER (2009) analysed 20 years of wet snow avalanche occurence in combination with metereological and snowpack data in the Dischma valley near Davos. They point out the relevance of snowpack parameters in wet snow avalanche formation. BAGGI (2005) summarizes in his thesis on wet snow avalanches that within the study area the number of wet slab avalanches decreases through spring time with increasing water penetration and increasing homogeneity (wet snow metamorphism) of the snowpack. The statistical analysis shows a significant correlation between capillary barriers in the snowpack and wet slab avalanche activity particularly during the first wetting of dry snowpacks. MITTERER (2012) estimated wet snow instabilities with a hydro-mechanical model and summarizes that 'at least one of the following three requirements have to be fulfilled: (1) If the snowpack is not in a sub-critical state (i.e. no weak layer exists in the dry snowpack), the amount of water has to be concentrated in order to develop instabilities. This might be due to ponding on more impermeable layers such as melt-freeze crusts or at capillary barriers. Also the interface snow-soil might act as capillary barrier. (2) If sub-critical conditions prevail, only small changes in liquid water content will affect stability. Timing of increased instability is fully determined by the low shear strength of the weak layer and the way water will reach the critical zone. (3) The stress due to loading is important when no prominent weak layer is present. In this case, the largest stress exists at the interface snow-soil. Combined with backed up water, this interface then represents a primary weakness.' McClung and Schaerer (2006) note that stored or geothermal heat can also produce water on the snowpack base (see also Moroz, 2002). They also report scattered thin wet slab avalanches releasing 'after slopes become covered by shadows as the sun sets. One explanation is that surface cooling causes the release of a slab that is already in tension due to water lubrication of an interface below the surface. Snow with low water content (as would be expected near the surface) is known to contract as it freezes, this effect can rapidly increase tensile stresses' (McClung an Schaerer, 2006). Moroz (2002) assumes that rapid warming of a dry cold snowpack causes different creep rates in midpack und upper layers, triggering full depth avalanches on a weak basal layer structure. Techel (2010) observed better ECT fracture propagation in wet snowpacks with melt-freeze crusts than in equal snowpacks with removed melt-freeze crusts. According to results of stability tests in wet snow conditions, Techel (2010) assumes that 'fracture propagation potential is highest when failure planes are composed of facets or depth hoar and is lower in well developed wet grains.'

Conway and Raymond (1993) studied several wet snow avalanche cycles triggered by rain on snow events in a maritime snow climate. They identified three evolutionary regimes of snow behavior associated to rain on snow events: (1) immediate avalanching with onset of rain; (2) delayed avalanching; (3) return to stability. Immediate avalanching only occured if the snow stability before rain was already close to critical. They also observed that snowpacks 'that have had time to strengthen during a slow warm-up are less susceptible to immediate instability' (Conway and Raymond, 1993). Possible reasons for immediate avalanching are increased stress on existing weak layers (before they are getting wet) through gravitational loading (precipitation), inertial loading (small surface avalanches from steep slopes or rock faces), loss of tensile strength of the slab or increased creeping (Heywood 1988) of the surface layer causing additional longitudinal stress. Another reason might be additional stress through rapid settlement of surface layers after wetting. However, settlement can also result in compensatory strengthening (CONWAY and RAYMOND, 1993). Possible reasons for delayed avalanching are additional stress through gravitational loading, reduction of shear strength through wetting of sub surface and basal weak layers - the wetting causes melting of grain bonds which reduces friction between grains. Additionally, rapid grain shape and texture changes due to wetting result in increased vertical and down slope strain contributing to instability. Previous avalanching and fully established drainage channels (also interrupting continuity of weak layers) contribute to increased stability (CONWAY et al. 2009) during continued rainfall before the entire snowpack becomes isothermal. If drainage channels are fully established, water output at the bottom of the snowpack can be observed (PEITZSCH et al., 2012b). Generally, a return to stability evolves, but full depth avalanches through water ponding at the snow ground interface are still possible. Cooling also contributes to increased stability by refreezing of ponded or flowing water in the snowpack.

BAGGI and SCHWEIZER (2009) are suggesting three triggering mechanisms for wet snow avalanches: '(1) loss of strength due to water infiltration and storage at capillary barrier, (2) overloading of partially wet (and weakened) snowpack due to precipitation, and (3) gradual weakening of (basal) snowpack due to warming of snowpack to 0°C and eventual failure of basal layers. Obviously, combinations of these three mechanisms may exist.' MCCLUNG and SCHAERER (2006) propose three principal release mechanisms for wet slab avalanches: '(1) loading by precipitation (rain), (2) changes in strength of a buried weak layer due to water, or (3) water lubrication of a sliding surface, which may be partially or totally impermeable to water. In cases 2 and 3, water may be added to the sliding surface by melt or rainfall' (MCCLUNG an SCHAERER, 2006). Conceptual approaches to wet snow avalanche release of TECHEL (2010), MITTERER (2012) and PEITZSCH (2009) are given in the following figures.

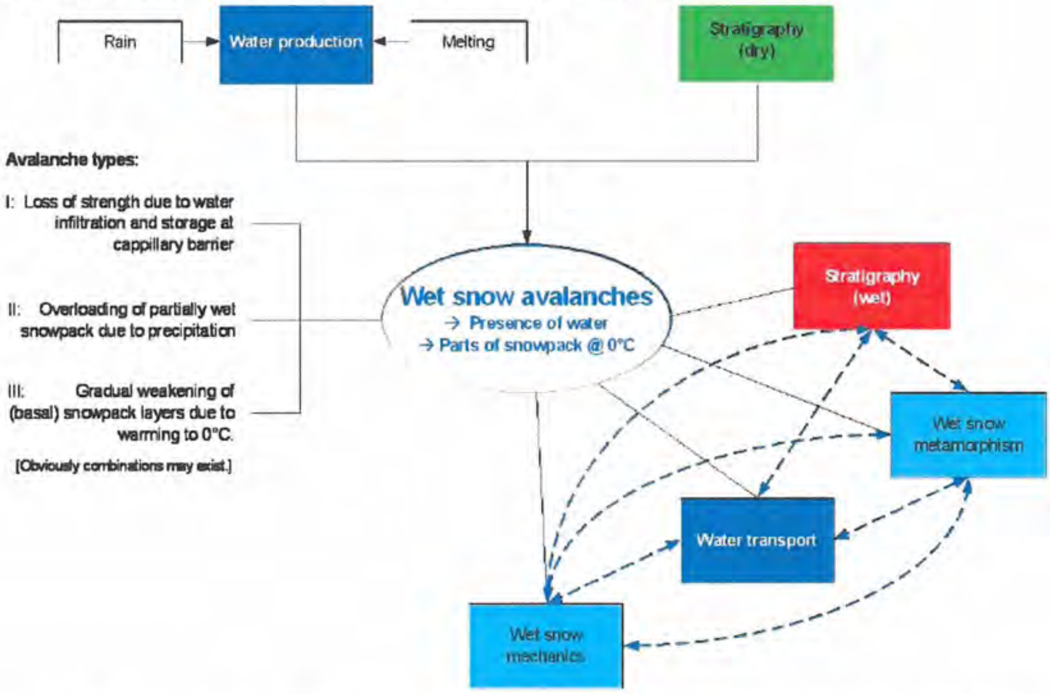
Obviously wet slabs are released because of reduced shear strength of layer interfaces (or snow-ground interface) and/or because of reduced compression strength of (basal) layers. Increased (tensile) stress through weight, settlement, creeping and/or reduced tensile strength of the slab are other reasons for wet slab release or might increase wet snow instabilities.

Figure 6: Wet snow stability evolution



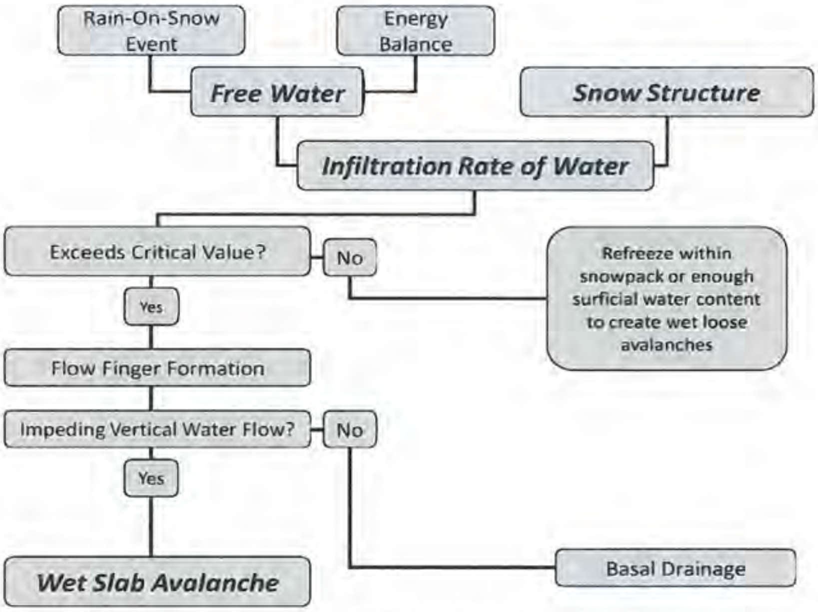
'A. Water penetrates surface layers. This causes a decrease in the strength of the slab, redistribution of longitudinal stresses and increased snow creep. If the snow stability is critical, avalanching may occur (failure plane in dry snow, mixed avalanches). B. Preferential flow reaches impeding layers or layer boundaries. Slope parallel flow reduces friction between grains. Failure may occur (wet avalanches). C. Gradual weakening of weak snowpack base due to water infiltration (wet avalanches). D. Return to stability if flow channels are well developed and the snowpack has fully metamorphosed to wet grains.' Source: TECHEL, 2010.

Figure 7: Conceptual model of wet snow avalanche formation



Conceptual approach of wet snow avalanche formation. 'There are two prerequisites for wet snow avalanche formation: (i) The presence of liquid water within the snowpack and (ii) parts of the snowpack are isothermal (0°C). The water production at the snow surface is determined by the energy balance and/or the delivered amount of water through rain.' According to BAGGI and SCHWEIZER (2009), three possible triggering mechanisms were suggested. 'It is not clearly understood how the response to added water influences wet snow instability. Obviously, for a given water supply, texture and stratigraphy control the rate of infiltration, the pattern of infiltration and the concentration of water at a given location - which then ultimately will affect the mechanical strength.' Source: MITTERER, 2012.

Figure 8: Conceptual model of wet snow avalanche formation



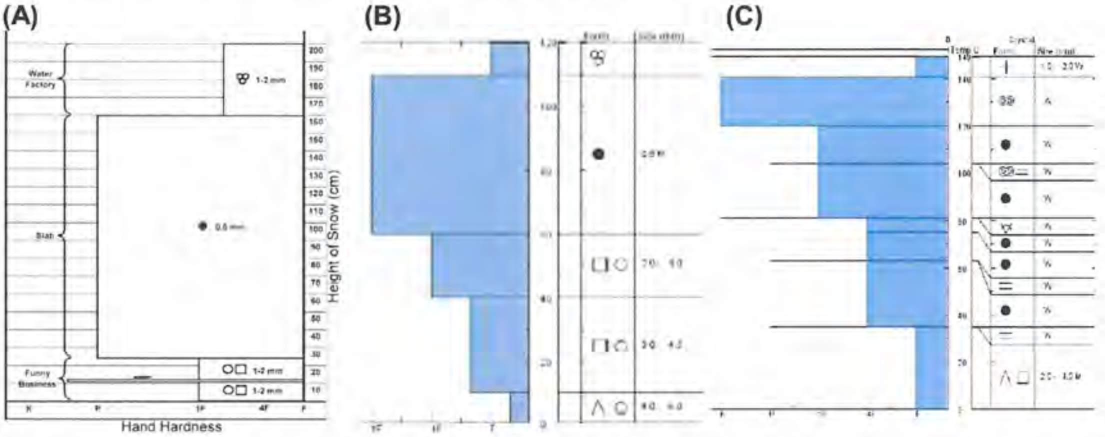
'Schematic detailing factors leading to wet slab production. As water infiltrates at a certain rate through the snowpack it exceeds a critical value where it begins to flow preferentially. When this preferential movement of water reaches a capillary barrier that is also a weak layer, a wet slab avalanche may occur.' Source: PEITZSCH, 2009.

A typical snow structure conducive to wet slab avalanches is presented by REARDON (2008) and has three components: a 'water factory' on top, a slab and 'the funny business' underlying the slab. In surface and near surface layers radiation and warm temperatures (or rain) are melting snow and creating liquid water. 'This component is roughly 50cm or less thick and composed of wet grains (1-3mm) that have undergone wet snow metamorphism. [...] The slab is the midpack layers. It is 75cm to 125cm thick and composed of small rounded grains with little to no water visible between grains. [...] Beneath these two components is 'the funny business.' This region is thinner, generally 30-50cm, with a significant weak layer present. It is composed of mixed grain types, generally coarser than the layer above. Grains at the ground may be large and have undergone some wet snow metamorphism due to above freezing temperatures. The grains of the weak layer are 1-2mm, and show some angularities and corners, though they might no longer be classified as faceted grains. In hand hardness tests, however, they feel like faceted grains' (REARDON and LUNDY, 2004). The 'funny business' is just one example of a failure plane / layer - often a weak snowpack basement (OSTERHUBER, 2006; TECHEL and PIELMEIER, 2009) can be found as failure layer. Other forms of weak layers forming a capillary barrier are also common like, for example, thin facets on an early winter midpack rain crust

(MOROZ, 2002). TRAUTMAN (2008) describes a similar type of wet slab triggered by rapid warming (or rain) 'before the snowpack lost its wintertime stratigraphy, and when an existing weak layer is activated by the addition of free water.' BAGGI and SCHWEIZER (2009) observed that wet slab avalanches are more likely in the first days after the isothermal state had been reached. PEITZSCH (2009) investigated two avalanche cycles: In one case, the snowpack consisted of coarse grained depth hoar under a fine grained buried rain crust (figure 9). 'It is likely that this layer impeded water flow and that the bonding within the layer of faceted grains/depth hoar was affected by the lateral movement of water at this interface' (PEITZSCH, 2009). In the second case, a merely damp slab was overlying a buried melt-freeze crust with wet old faceted grains above. 'This structure illustrates how water may move preferentially through the slab allowing the upper part of the snowpack to retain slab-like characteristics by keeping it mostly dry or only slightly moist' (PEITZSCH, 2009). MARIENTHAL et al. (2012) observed a well pronounced depth hoar layer as trigger for historic wet slab avalanches. BROWN (2008) observed two distinct types of layering, both of them capable of producing wet slab avalanches: The first type (figure 9) agrees with the schematic profile of REARDON and LUNDY (2004).

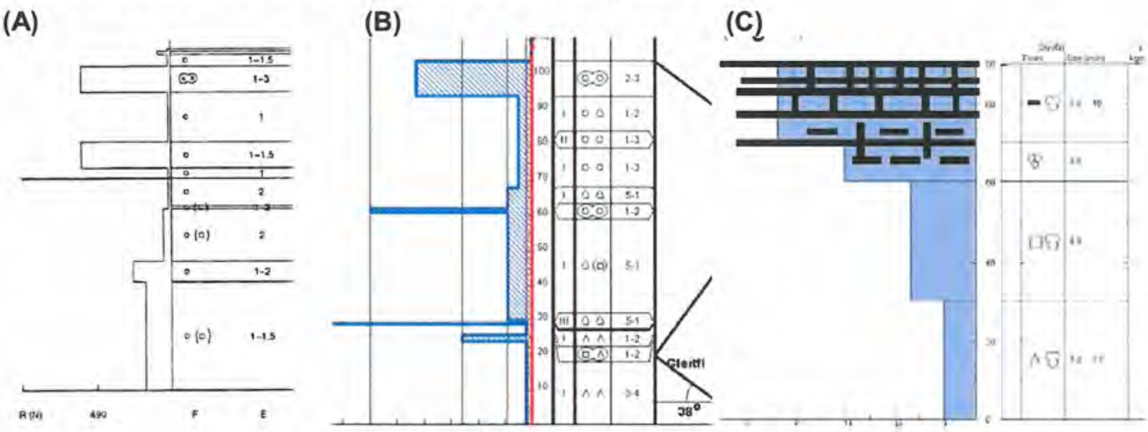
'The second type of layering pattern (figure 10) involved a slab layer present in the top 20-40cm of the snowpack that had abundant vertical and horizontal ice masses present from diurnal melt-freeze cycles. This M/F 'slab' typically set on top of large M/F polycrystals that were poised above the wetted basal facets or depth hoar. The stratigraphy seen in pattern (B) would be associated with a 'mature' old well wetted snowpack' (BROWN, 2008). Figure 10 also shows a similar type of wet snow avalanche in a ripe snowpack observed by FIERZ and FÖHN (1994) and some years later by TECHEL (2008) at the same slope. Analysis of fracture line and unstable slope profiles of TECHEL and PIELMEIER (2010) show similar characteristics: The slabs 'overlying the failure plane were moist or wet, relatively soft and consisted of coarse MF-forms, although precipitation and round particles were also observed' (TECHEL and PIELMEIER, 2010). Compared to stable slope profiles, unstable slopes are wetter and softer and have undergone considerable wet snow metamorphism. 'Typically avalanche failure planes are in, or adjacent to, very soft, coarse grained layers consisting of persisting grain forms or wet grains with remnants of persistent grains still recognizable' (TECHEL, 2010).

Figure 9: Wet snow instabilities in transitional wet snowpacks



(A) Schematic profile of snow structure during a wet slab avalanche cycle (Source: REARDON and LUNDY, 2004). (B) Typical stratum with a moist midpack slab present (Source: BROWN, 2008). (C) Crown profile of a wet slab avalanche released during a first major warming event. 'The failure layer is a mix of depth hoar and large grained faceted crystals under a thin ice crust' (Source: PEITZSCH, 2009).

Figure 10: Wet snow instabilities in fully-wet snowpacks



(A) Simplified snow cover profile taken in the starting zone of a wet snow avalanche released 1993 on Dorfberg. The gliding plane was formed by a thin ice lamella lying at a height of 73 cm (Source: FIERZ and FÖHN, 1994). (B) Snow cover profile taken one day after release of a wet snow avalanche on Dorfberg 2005 (Source: TECHEL, 2008). (C) Typical stratum prone to wet snow avalanches in a well matured, output-phase snowpack (Source: BROWN, 2008).

Obviously wet snow avalanches can release in fully-wetted snowpacks (figure 10) that have already undergone wet snow metamorphism and transitional snowpacks during the first serious wetting (figure 9). However, the delineation between those release types is fluent, transitional types may exist.

Wet slab avalanches are generally difficult to predict because of the relatively short time window (PEITZSCH, 2008). 'The right conditions for the release of a wet slab avalanche might prevail for a shorter time (hours) than in the case of dry snow slab avalanches which may release on weak layers that persist for days, or even weeks' (BAGGI and SCHWEIZER, 2009). In wet snow conditions snow is exactly on its melting point 'and can change its properties suddenly' (WIESINGER et al., 2013). Avalanche control must be performed when the snow is sufficiently unstable so that it can be released and yet before avalanches occur naturally (CONWAY et al., 1988). According to his observations on wet snow instability during rain, HEYWOOD (1988) states that 'explosive control of rain on snow avalanches was found to be effective if applied within a critical time period.'

2.3.2 Wet loose snow avalanches

Wet loose snow avalanches release because of the loss of strength between all of the snow grains in the upper snowpack layers (KATTELMANN, 1984) through wetting with melt water or rain. Wetting occurs when the snowpack cannot effectively drain meltwater resulting in water accumulation in the surface layer (REARDON and LUNDY, 2004). 'For either dry or wet loose snow avalanches, the basic principle is the same: The slope angle exceeds the critical angle (called the angle of repose or static friction angle) necessary to cause motion. A static friction angle may be defined for each type of snow to initiate downslope motion depending on grain geometry, temperature, cohesiveness and water content' (MCCLUNG and SCHAERER, 2006). Wetting causes a loss of cohesion and decrease in friction angle towards 35° (MCCLUNG and SCHAERER, 2006). According to BAGGI (2005), wet loose snow avalanches are more associated with well consolidated basal snowpacks than wet slab avalanches. TRAUTMAN et al. (2006) measured surficial shear strength with a shear frame during melt-freeze cycles and observed a relation to wet loose snow avalanche activity: 'When our shear strength measurements dropped below 250 Pa, we observed and triggered wet loose avalanches in the immediate vicinity of study slopes.' Shear strength decreased on all of the four test days during daytime warming, but avalanche activity was only observed when the treshold value was reached. Depending on the grain forms in upper layers, TRAUTMAN (2008) differentiates between new snow and old snow wet loose snow avalanches: Larger grain sizes drain better due to reduced capillary action, therefore, more energy (or rain) is needed to create excess water overwhelming the existing drainage capacity.

2.4 Weather situations and wet snow instabilities

'Per definition, the potential for wet avalanches is absent as long as the entire snow cover is below 0,0°C' (ARMSTRONG, 1976). As soon as at least parts of the snowpack get isothermal the probability of wet snow avalanches depends on the amount of liquid water available in the snowpack. Different weather situations can lead to water input into the snowpack: Energy input through warming and radiation into the top snowpack layer leads to melting of snow and creation of liquid water. Warming and radiation during spring melt season are the most common triggers for wet snow avalanches in transitional and continental snow climates. Whereas water input into the snowpack through rain on snow events, wet snowfall or midwinter snowmelt are common triggers in maritime snow climates (KATTELMANN, 1984). BAGGI and SCHWEIZER (2009) analysed a 20 year dataset of avalanche activity in the Dischma valley near Davos. The results suggest that wet slab avalanches primarily occur during or shortly after a significant increase in air temperature, during periods of warm weather and during or shortly after rain or snowfall in transitional snowpack regions. ROMIG et al. (2004) suggest to differentiate between wet snow instabilities associated with and without recent new snow in the past 48 hours, 'because instabilities in new snow may be influenced more by early warming or solar radiation events, while old snow may require more prolonged warming or solar radiation before instabilities develop.'

Wet snow avalanches are difficult to forecast (MITTERER et al., 2009). According to a survey of TECHEL and PIELMEIER (2009), 'major forecasting problems concern the timing of avalanche release, in particular the onset of avalanching.' But determining the peak and end of wet snow avalanche periods is also difficult (MITTERER and SCHWEIZER, 2013a). Once the snowpack becomes isothermal and stability is close to critical, metereological parameters are important in forecasting wet snow avalanches. Several studies investigated the relationship between meteorological factors and wet snow avalanche release.

ARMSTRONG (1976) used air temperature as an indicator for wet snow avalanche days. Other studies (MCCLUNG and TWEEDY, 1994; HARTMAN and BORGESON, 2008; BROWN, 2008; SKORIC, 2013) also observed temperature variables as an indicator for wet snow avalanche activity. But according to TRAUTMAN (2008), air temperature is more an indicator than a discrimination factor: 'Experiences and research have shown that monitoring air temperature is only partially useful when forecasting wet snow avalanches' because of overlapping data ranges for avalanche and non avalanche days. Nevertheless, investigations by BAGGI and SCHWEIZER (2009) showed that avalanche activity is significantly related to air temperature variables. MITTERER et al. (2009) analysed two distinct wet snow avalanche cycles which occured in the area of Davos and observed the rapid increase in air temperature as a key parameter leading to wet snow instability.

Rain is a common trigger of wet snow instabilities predominantly in maritime snow climates (HEYWOOD, 1988). Defining treshold amounts and intensities for precipitation events triggering wet snow avalanches is not possible and strongly depends on snowpack structure: Avalanche activity can increase immediately after the onset of rain when slope stability is close to critical but may be delayed when rain falls on a more stable snowpack (CONWAY and RAYMOND, 1993; CONWAY et al. 2008). Precipitation events are also possible triggers for wet snow instabilities in alpine regions. BAGGI and SCHWEIZER (2009) observed the amount of precipitation as a significant parameter related to wet snow instability. MITTERER et al. (2009) observed additional loading by snowfall and input of melt water due to rain in combination with a rapid warming as triggers for a large avalanche cycle.

According to investigations by BAGGI and SCHWEIZER (2009) 'radiation variables had no discriminating power as there was hardly any difference in radiation between avalanche and non-avalanche days.' However, BORGESON and HARTMAN (2010) found treshold values for incoming radiation leading to melt water production and increased avalanche potential in combination with temperature and humidity indices. SKORIC (2013) observed tendencially higher radiation income on days with wet snow avalanche activity. MITTERER and SCHWEIZER (2013a) observed radiation parameters significantly related to wet snow avalanche activity. Predictive performance improved by implementing other meterological and snowpack parameters through multivariate statistics (MITTERER and SCHWEIZER, 2013a). Best predictive results were provided through calculating the energy balance (MITTERER and SCHWEIZER, 2013a). The calculation of the energy balance is complex because multiple meterological, topographical and snowpack parameters have to be considered. The energy balance of the snow surface is the sum of the net radiation input (short wave and long wave radiation), the sensible heat exchange, the latent heat flux, the ground heat flux and the advective heat flux through mass transfer of energy into snow - for example rain on snow (TRAUTMAN, 2008). 'Once the temperature of the snow surface is raised to 0°C, further energy input results in the conversion of ice to liquid water' (TRAUTMAN, 2008). MITTERER and SCHWEIZER (2013a) calculated energy balance with the snow-cover model SNOWPACK (BARTELT and LEHNING, 2002) to predict periods with high wet snow avalanche activity: 'Wet snow avalanche activity was closely related to periods when large parts of the snowpack reached an isothermal state and energy input exceeded maximum value of 200 kJ m^{-2} in one day, or the 2-day sum of positive energy input was larger than 1,2 MJ m^{-2}.' Calculated energy balance showed up as best predictors for wet snow instability (MITTERER and SCHWEIZER, 2013a). Compared to punctually measured meterological variables, the calculated energy balance can better take into account different aspects, slopes and elevations (MITTERER and SCHWEIZER, 2013a).

Different approaches in numerical avalanche prediction have been developed for forecasting avalanche activity. Three basic principles of avalanche forecasting systems are differentiated: expert systems, statistical and deterministic methods (BRABEC, 2001; NAIRZ, 1997). Statistical methods include, for example, nearest neighbour models, cluster analysis, classification trees, regression and discriminant analysis (examples given in: KLEEMAYR et al., 2000; FROMM, 2009; GASSNER et al., 2000; BUSER, 1983; SKORIC, 2013). Expert systems include fuzzy-expert systems or neural nets (examples given in: KLEEMAYR et al., 2000; BOLOGNESI, 1993; SCHWEIZER and FÖHN, 1994). Deterministic avalanche forecasting models are based on physical based snowpack simulation models (for example SAFRAN-CROCUS-MEPRA, DURAND et al., 1999). Depending on the approach, input data is based on metereological data, snowpack data and/or historic avalanche data. Most of the forecasting models are focusing on dry snow avalanches. Recently some studies were focusing on numerical forecasting of wet snow avalanches. ZISCHG et al. (2005) developed a fuzzy logic rule based expert system that generates a dynamical hazard index map on a regional scale. ROMIG et al. (2004) and PEITZSCH et al. (2012b) developed statistical forcasting models based on several input parameters to predict wet snow instability. However, statistically based forecasting models are only suitable for the region for which they are developed and they are only a supporting tool in the forecasting process but cannot replace the decision making of avalanche professionals (ROMIG et al., 2004).

3 Artificial release of avalanches

According to the classification of avalanche protection measures (MARGRETH and BURKARD, 2010), artificial release of avalanches is a so called short-term active mitigation measure. The objectives of artificial avalanche release within an avalanche safety concept are the controlled release of avalanchs to reduce closure times, the testing of the instability of the snowpack, the frequent release of avalanches to reduce the amount of snow in the starting zones and, thus, to reduce the risk of potential big avalanches (STOFFEL, 2001; MCCLUNG and SCHAERER, 2006; LAND TIROL, 2001). In this chapter the impact of explosives on the snow cover, different artificial release methods and the procedure of control operations are summarized.

3.1 Impact of explosives on the snow cover

According to GUBLER (1977) 'the general aim of blasting is to diminish stability on an inclined snow cover by increasing stress, by decreasing strength, or by a combination of the two.' In dry snow conditions mainly slab avalanches are artificially released by triggering a slab overlying a widespread weak layer. SCHWEIZER et al. (2003) provide a detailed overview of dry slab avalanche formation. Depending on the slab properties and its deformation velocity, more or less stress acts on the underlying weak layer. If a treshold value in deformation velocity is reached, the deformation in the underlying weak layer provokes enough bond breaking that initial ductile shear fractures occur locally within the weak layer - so called hot spots (GUBLER et al., 2012). Increasing stress on the snowpack increases the number of hot spots, connects them through ductile fracturing and finally leads to a brittle shear fracture propagation within the weak layer, followed by a tensile fracture at the crown, resulting in a slab avalanche. One potential source of additional stress is the impact of explosives. In wet snow conditions slab and loose snow avalanches are artificially triggered. Release mechanisms are more diverse (see chapter 2.3) and poorly understood because of the complexity of the mechanical and physical behaviour of wet snow. However, fracture propagation potential of wet snow is generally lower than in dry snow conditions (see chapter 2.2). Conclusively, more energy is needed for fracture initiation and propagation (SKORIC, 2013).

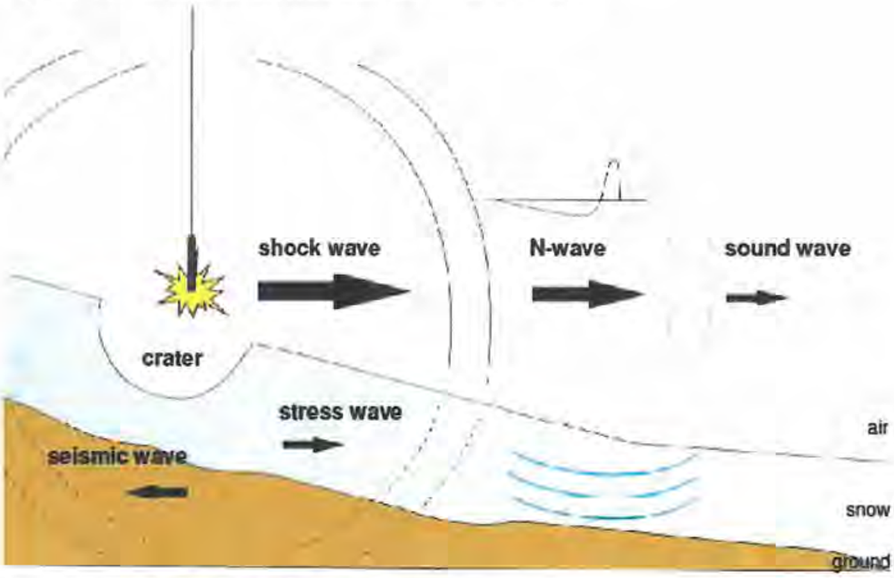
The timing of the avalanche control operation is crucial: 'To be effective, avalanche control must be performed when the snow is sufficiently unstable so that it can be released with explosives or by ski-testing and yet before avalanches occur naturally' (CONWAY et al., 1988). Whereas in dry snow conditions the criticial conditions often persist over a longer time period - several hours or even days (or weeks) - conditions may change very fast in wet snow situations, 'because the material snow is exactly on its melting point and can change its properties suddenly' (WIESINGER et al., 2013).

'The effect that an explosive has on its surroundings depends on the impulse (integrated pressure over time) and maximum pressure that is generated upon detonation' (JOHNSON, 1994). A detonation or explosion causes a high pressure shock wave. The snow cover is influenced by the shock waves through a direct push causing a crater in the snowpack (CHERNOUSS et al., 2006). Within the snow cover the shock waves propagate as stress waves (longitudinal P- and transversal S-waves) with mainly radial and slope parallel oscillations (GUBLER, 1977). Porous materials such as snow are very effective energy absorbers. Therefore, stress waves attenuate very rapidly in the snowpack. The propagation of stress waves within the snowpack is limited. 'Most of the energy is absorbed in the crater zone' (GUBLER, 1977) and the impact of stress waves is limited to the immediate vicinity around the crater (UELAND, 1992). JOHNSON et al. (1994) observed maximum shock wave attenuation in seasonal snow (250 kg m^{-3}), proportional to the propagation distance x, between $x^{-1,6}$ and $x^{-1,5}$ for plane waves and x^{-3} for spherical waves.

Above the snow surface the shock wave develops almost immediately into an N-shaped pressure wave with vertical oscillations (GUBLER et al., 2012). The N-shaped pressure waves propagate over the snow cover with velocity of sound and entering the snowpack through the pore system. N-shaped waves finally develop into sound waves (GUBLER et al., 2012). Air is a much more efficient medium for transmitting shockwaves. 'This N-wave acts through the pore system of the snow resting on the ice skeleton and excites strongly damped oscillations in the snow cover' (GUBLER, 1977). UELAND (1992) classifies those N-waves as P-waves / sound waves producing a transverse S-wave within the snowpack. According to JOHNSON et al. (1994), the attenuation of spherical waves in air over snow is proportional to about x^{-1}.

CHERNOUSS et al. (2002) studied seismicity-induced avalanche releases. Explosives also induce seismic effects. 'Because of the ground's higher density, the ground waves would attenuate at a slower rate than the air waves' (UELAND, 1992) and, therefore, they may travel much further than N-waves. However, with regard to avalanche release, ground waves were shown to be insignificant under most conditions because of their small amplitudes - even when charges were detonated on the ground surface (UELAND, 1992; JOHNSON et al., 1994).

Figure 11: Impact of explosives on a snow cover



Source: GUBLER et al. 2012 (translated).

Within the effective range the explosive-induced stress is higher than the treshold stress needed to trigger an avalanche. 'Knowing the stability and strength of the snow cover, we are able to estimate the additional stress which has to be created by the stress wave' (GUBLER, 1977) to artificially release an avalanche. According to GUBLER (1977), the attenuation of impact waves and the effective range can be described as a function 'of the type of explosives used, the position of the charge relative to the snow surface, the charge mass, the snow stratification profile and the type of ground' (GUBLER, 1977). Resulting effective ranges are shown in table 1.

The position of the detonating charge, relative to the snow surface, influences the propagation of shock waves, stress waves and N-waves. Experiments of UELAND (1992) and GUBLER (1977) show that air blasts produce 'slightly larger shockwaves than surface blasts, while buried shots produce much smaller shockwaves than air or surface blasts' (UELAND, 1992). TICHOTA et al. (2010) also observed higher snowpack response to air blasts. According to GUBLER (1977), N-waves of charges fired within the snowpack have reduced peak pressure by 1 to 2 orders of magnitude. Measurements of UELAND (1992) show that the wave amplitudes of airblasts (1 m above snow surface) are on average 10-15% greater than surface shots. The wave amplitude is about half for buried charges (25 cm below snow surface). Attenuation is proportional to the distance the charge is below the snow surface (UELAND, 1992). The best effective range can be reached with detonation heights of between 1,5 m to 5 m depending on the charge size (JUERGENS, 1984). JOHNSON et al. (1994) propose to calculate the detonation height H for explosives of weight w with '$H = w^{1/3} \times H_{max}$', 'where H_{max} is the detonation height of an explosive that produces the maximum pressure at a given radius' (JOHNSON et al., 1994), with proposed values between 1 and 2 m $kgf^{1/3}$. Increased detonation heights have little additional effect on increasing maximum snow surface pressure. 'As the detonation height above the snow cover is increased the pressure at ground zero will decrease' (JOHNSON et al., 1994). Therefore, a 'compromise must be found between the shock wave intensity and the impacted surface: A distributed average shock on a larger surface or a punctual maximum shock' (BERTHED-RAMBAUD, 2009). A punctual maximum shock may be required to release deep and hard slabs (MCCLUNG and SCHAERER, 2006).

According to UELAND (1992), harder snowpacks attenuate shockwaves less than softer, less dense snowpacks. However, 'the shockwave attenuation rate in snow seems to be more directly related to the snow's hardness than to the snow's density' (UELAND, 1992). Softer ice grains seem to absorb more energy than harder ice grains because harder ice grains transmit more energy to neighbouring grains (UELAND, 1992). In soft new snow the shockwave attenuation rate is very high (MIKLAU and SAUERMOSER, 2011). Experiments of GUBLER (1977) indicate that N-waves penetrate, almost unchanged, into the pore system of the snow cover in dry snow conditions. In wet snowpacks N-waves attenuate strongly (GUBLER, 1977). Measurements of UELAND (1992) agree with these findings. The pore water and softer ice grains in isothermal snowpacks seem to attenuate the penetrating N-waves. Buried charges in moist or wet snow do not have a widespread effect beyond the crater (TICHOTA et al., 2010).

The placement of explosives within the starting zone is crucial. The topography of the starting zone influences the placement. Only 'those locations of the snow cover within the potential effective range are tested/loaded that can be seen from the position of the charge' (GUBLER and WYSSEN, 2002). To secure an avalanche release zone, the whole potential release zone has to be tested with explosives (GUBLER and WYSSEN, 2002). Depending on the effective range of the release method and the actual snow and stability conditions, number and positioning of charges within the release zone vary.

Investigations by JOHNSON (1994) and LIVINGOOD et al. (1990) show greater effects with increased charge masses with a 'diminishing efficiency as the mass is further increased' (JOHNSON, 1994). Experiments of UELAND (1992) showed an increased area of influence by a factor 1,44 for doubling charge size from 1 kg to 2 kg. According to investigations by GUBLER (1977), the effective range of a charge mass (w) increases proportional with $w^{1/2}$ in dry and $w^{1/4}$ in wet snow conditions for charge masses between 1 and 10 kg (GUBLER et al., 2012). Depending on the charge position relative to the snowpack surface, displacement velocity is proportional to $w^{0,66\text{-}0,69}$ for charges in the snow cover and to $w^{0,7\text{-}0,75}$ for charges on or above the snow surface (GUBLER, 1977). The shock wave and N-wave amplitudes were also higher in parts of the affected area when using bigger charges. This may indicate that 'using fewer large charges can be more efficient than using a larger number of smaller charges' in dry snow conditions. PERLA and EVERTS (1983) observed a significant increasing probability of avalanche release with increasing bomb mass. According to MIKLAU and SAUERMOSER (2011), generally charge sizes between 1 kg and 5 kg are used in Austria. For isothermal and wet snow conditions UELAND (1992) recommends larger charges.

Generally, explosives with detonation velocities of between 5000 m/s and 8000 m/s are used for artificial avalanche release (PERLA, 1976). MCCLUNG and SCHAERER (2006) recommend explosives with high detonation velocities of between 5000 m/s and 7000 m/s for charges placed on or above the snow surface and slower detonation velocities of between 3000 m/s and 4000 m/s for charges inside the snow. According to GUBLER et al. (2012), lower detonation velocities with higher gas release are more appropriate inside the snowpack. However, following the theory of JOHNSON

(1994) explosive effectiveness is only influenced by the specific energy and mass of explosives and not directly by detonation speed. But GUBLER (1977) observed increased displacement velocities within the snowpack by a factor of 2 compared to charges with detonation velocities of 2000 m/s and 7000 m/s. According to JOHNSON (1994) 'the perception that high detonation speed explosives are more effective than low detonation speed explosives at causing snow avalanche failure is a result of comparing explosives with equivalent mass rather than equivalent total energy.'

Depending on the gas mixture, different durations of the shock waves may result for gas exploders (BERTHET-RAMBAUD, 2009): A hydrogen-oxygen mixture has a twice shorter explosion duration than a propane-oxygen mixture (BERTHET-RAMBAUD et al., 2008). Compared to explosives, the shape of the pressure curve of gas exploders includes 'a very deep depression zone just after the shock wave itself' (BERTHET-RAMBAUD, 2009). During the depression the snowpack may be lifted to easily start moving (BERTHED-RAMBAUD et al., 2008). However, the effect of the depression on avalanche release is not investigated in detail yet.

According to calculations of GUBLER (1977) 'the effective range for shots above the snow surface is 17 to 120 m for 1 kg charges depending on the slope stability.' In the guideline for artificial avalanche release, STOFFEL (2001) differentiates between effective ranges of explosives generating safety for natural avalanche releases (fracture safety) and safety for skiing triggered releases (skiing safety). Within the effective range for fracture safety, the detonation has to reach a minimum surface pressure of 100 Pa in order to decrease the risk for naturally triggered dry snow avalanches beyond an acceptable treshold value (GUBLER et al., 2012). For starting zones that are skied immediately after the control operation the minimum pressure has to be set to 200 Pa (GUBLER et al., 2012). According to GUBLER et al. (2012), the deformation velocity within the snowpack is a more reliable parameter to compare explosives and gas devices than the induced snow surface pressure. The additional stress within the snowpack is proportional to the density and deformation velocity (GUBLER et al., 2012). The deformation velocity within the snowpack is strongly related to the N-wave pressure increase within the pore system. According to measurements of GUBLER et al. (2012), 4 kg of explosives induce a pressure increase of about 0,67 kPa/ms with an additional stress of about 900 Pa in the snowpack within a distance of 80 m to ground zero. A 4,5 m³ propan dioxygen mixture only induces a pressure increase of about 0,09 kPa/ms and additional stress of 100 Pa within a distance of 110 m to ground zero (GUBLER et al., 2012). A detailed overview of effective ranges in dry snow conditions is given in table 1.

Table 1: Overview of effective ranges

	Charge size	Effective range in dry snow conditions (fracture safety)	Effective range in dry snow conditions (skiing safety)
Explosives - detonation in snowpack			
charge ~ 0.2 m below snow surface	4 - 5 kg	40 m	25 m
charge ~ 0.2 m below snow surface	1,5 - 2,5 kg	25 m	15 m
charge ~ 0.7 m below snow surface	1,5 - 5 kg	10 m	5 - 10 m
Explosives (with high detonation velocity) - detonation on snowpack			
charge on snow surface	4 - 5 kg	50 - 60 m	30 - 35 m
charge on snow surface	1,5 - 2,5 kg	35 - 40 m	20 - 25 m
Explosives (with high detonation velocity) - detonation above snowpack			
charge ~ 3 - 3,5 m above snow surface	4 - 5 kg	120 - 130 m	70 m
charge ~ 2 - 2,5 m above snow surface	1,5 - 2,5 kg	80 - 90 m	50 m
charge ~ 1 m above snow surface	4 - 5 kg	80 - 90 m	50 m
charge ~ 1 m above snow surface	1,5 - 2,5 kg	60 - 70 m	35 - 40 m
Gas exploders			
Gazex (in tube direction)	3 m³	70 m (- 120 m)	35 m - 84 m
Gazex (in tube direction)	1,5 m³	50 m (- 100 m)	25 m - 70 m
Gazex (45° out of tube direction)	3 m³	50 m (- 100 m)	25 m - 70 m
Projectile devices			
mortar 8,1 cm	0,6 kg	15 - 20 m	10 m
rocket-tube 8,3 cm	0,7 kg	20 - 25 m	10 - 15 m

Sources: own illustration completed with information from GUBLER, 1976; GUBLER et al., 2012; STOFFEL, 2001.

In wet snow conditions the effective range is limited to the area around the crater zone (STOFFEL, 2001). The impact is limited to the shock wave because N-waves attenuate very fast in fully-wet (GUBLER, 1977) and soft snowpacks. Additional stress cannot reach the already higher treshold value for fracture initiation in wet snow conditions. However, there are no detailed studies on effective ranges in wet snow conditions. The impact of explosives in wet snow conditions may also differ according to the wetness stage and predominant release mechanism.

3.2 Artificial release methods

Artificial release methods can be classified into explosive-based methods, gas exploders and mechanical release methods. Methods that are currently in use in Austria or Switzerland are listed in table 2. Generally, autonomous devices do have the highest investment costs. Operating costs and maintenance costs differ between the listed methods. As the present study is not focusing on the costs of different release methods, they are not discussed in detail.

To find the appropriate release method to control a specific avalanche area, at least a cost-effectiveness analysis should be carried out in the design process of an avalanche safety concept. Depending on location and protection goal, other factors like maintenance, operation reliability, landscape impact, waste, duds or safety of ski patrollers might be discussed throughout the development of an avalanche safety concept.

Explosive-based release methods usually use powder, slurry or gelatinous explosives - specially composed for artificial avalanche release (low temperature application). If methods use other explosives, they are shown in brackets (table 2). Usually, charges from 1 to 5 kg are used (MIKLAU and SAUERMOSER, 2011). Gas exploders use a propane and dioxygen mixture or a hydrogen and dioxygen mixture (Daisy Bell, O'bellx) (LIEBERMAN, 2002; STOFFEL, 2013). The effective range of the listed mechanical triggers is limited to the immediate impact area.

To complete the measures listed in table 2 some additional artificial release measures that are not used (any more) or are not permitted in Austria and Switzerland are mentioned in the following list:

- Avalhex (DUCLOS and SENABRE, 2002) - not produced any more.
- Avalhex Heli - not produced any more.
- Preplanted charging (PERLA and EVERTS, 1983) - not permitted.
- Vibrating plate/table - not in use.
- Aerially deployed water drops (REARDON and LUNDY, 2004).

Table 2: Overview of artificial release methods and their technical characteristics

	Limitation charge **size**	Limitation **number** of charges	Detonation **in** snowpack	Detonation **on** snowpack	Detonation **above** snowpack	**Flexible** release point	**Range**	**Remote** control	Placement **accuracy**	**Duration** of control operation
Explosives - hand delivery										
with / without rope			X			x	+[1]		++	~
on a pole					X	x	+[1]		++	~
rotating arm					X		•		++	~
Sledge				X		x	+[1]		++	~
out of cableway			X		x	x	----		+	+
helicopter charging			X			X	++[2]		+	++
Explosives - ropeways										
Ropeway (manual)		1			X	x	----		++	~
Ropeway (motorized)		1			X	x	----		++	~
with charge dropper	up to 5 kg	2/4			X	x	----		++	+
Explosives - towers										
avalanche guard (blaster box)	2,7/5,4 kg	10	X			x	150 m	X	~	++
avalanche tower (Inauen Schätti)	2,7/5,4 kg	10			X		•	X	++	++
avalanche tower (Wyssen)	5 kg	12			X		•	X	++	++
mini avalanche tower (Wyssen)	5 kg	4			X		•	X	++	++
Explosives - projectile delivery										
avalanche pipe	2,7 kg		X			x	500 m		~	~
avalancheur (2-phase liquid explosives)	2,2 kg			X		x	2 km		~	~
lawin locker 'Großer Bär' (pyrotechn.)[3]	1-1,5 kg			X		x	850 m		~	~
lawin locker 'Murmel' (pyrotechn.)[3]	1-1,5 kg			X		x	350 m		~	~
lawin locker 'Fellow' (pyrotechn.)[3]	1-1,5 kg			X		x	450 m		~	~
mortar (military; TNT)[3]	0,6/3 kg		X	x		x	6 km		~	~
rocket-tube (military; Oktasit)[3]	0,7 kg		X	x		x	1,2 km		~	~
Gas exploders										
Gazex	0,8-3 m^3	var.			X		•	X	++	++
Gazflex	0,8-1,5 m^3	var.			X		•	X	++	++
O'bellx	~1,5 m^3	50			X		•	X	++	++
Daisy Bell	0,8 m^3	50			X	X	++[2]		+	++
Mechanical triggers										
groomer						x	+		++	~
ski cutting						x	+[1]		++	~
tilt table							•		++	/

[1] requires safe access for ski patrollers; [2] requires good weather conditions; ~ + ++ classification schema (/ not classified); ---- linear installation; • punctual installation; X available, possible; x possible with limitations; [3] military weapons are not permitted in Austria, lawin locker has no permission for Switzerland.

Source: own illustration completed with information from BÉRARD and BORREL, 1994; BERTHET-RAMBAUD, 2008; BUCHINGER, 2014; GUBLER and WYSSEN, 2002; GUBLER et al., 2012; INAUEN SCHÄTTI, 2012; INNERKOFLER, 1999; LIEBERMAN, 2002; MIKLAU and SAUERMOSER, 2011; PERLA and EVERTS, 1983; STEINLEITNER, 2013; STERBENZ, 2002; STOFFEL, 2001; STOFFEL, 2013.

As mentioned in the previous chapter, the impact of the explosives on the snow cover depends on the size of the explosives, the type of explosives, their location relative to the slope (placement) and snow surface (position) (STOFFEL, 2001; MCCLUNG and SCHAERER 2006). Depending on impact factors, the effectiveness of the different release methods, listed in table 2, can be assessed. For the artificial release of dry snow avalanches, methods with big charge size, detonation position above snowpack and high detonation velocity are most effective (GUBLER, 1977; STOFFEL, 2001; MCCLUNG and SCHAERER, 2006).

Successful frequent artificial release of dry snow avalanches indirectly affects the activity and size of wet snow avalanche within the same starting zone: 'The purpose is to avoid problems with wet snow spring avalanches [...] by reducing the snow cover in the release zone [...] by routine blasting during winter' (GUBLER and WYSSEN, 2002). A similar effect is described by GIBSON et al. (2000) in context of rain on snow effents. MCCLUNG and SCHAERER (2006) summarize that 'frequent avalanche release prevents large unpredictable natural avalanches later, for example, with snowmelt.'

Whereas the impact factors are well defined for the artificial release of dry snow avalanches, they are presently not studied in detail for the different types of wet snow avalanches. Thus, the different methods cannot be evaluated to their effectiveness for wet snow avalanche release. Whether literature nor promotion material of manufacturers give information about the application of different release methods in wet snow conditions.

Anyway, there are some trigger techniques for hand charging described in studies of MACHIDA et al. (2008a) and MACHIDA et al. (2008b): They introduce and describe a method with raster-based positioning of many small charges in drilled hollows within the starting zone to release wet snow avalanches. A similar concept is described by ISREALSON (1976). He describes a technique planting charges along a line across the slope connected with detonating cord. The pre-placement of the charges is done during safe snow conditions in the morning. Other trigger techniques are described by FERGUSON (1985): 'Wet-slabs do seem to respond to added shearing motion, however. For instance, one common triggering technique is to induce a loose avalanche above a suspected slab region by firing into rocks or loose snow. This will then flow over the lower elevation starting zone and help trigger the slab avalanche.

Small wet-slabs respond to the swooping motion of a broad turning skier also.' She also describes the pre-placement of large explosive charges at the bottom of potential release zones with variable release success.

3.3 Avalanche control services and control operations

Avalanche control services are established by mountain communities, ski areas, road administrations or other infrastructure authorities, for example, railways, power plants and power supply networks. They are assessing the local avalanche danger and making recommendations to the authorities on how to best protect people and infrastructure (STOFFEL and SCHWEIZER, 2008). Possible protection measures include the whole range of short-term avalanche protection measures. The applicability of artificial avalanche release depends on existing values and damage potential in the respective avalanche path and runout zone. Safety concepts, avalanche maps and hazard maps are basic requirements for managing avalanche hazard in a temporary context. Those documents are predesigned by consultants, authorities or by the avalanche control services themselves. For ski areas those documents are already necessary in the permission process of new ropeways (ZECHNER, 2011). Safety concepts include, for example, the procedure of artificial avalanche release including necessary closures, communication and avalanche maps with release points and available methods. Organisational prerequisites for avalanche control services include, among others, structure and responsibilities, education of the members, interfaces with neighbouring avalanche control services and insurances (STOFFEL, 2001; STOFFEL, 2004).

The following guidelines document the state of art in the daily routine avalanche hazard management. STOFFEL and SCHWEIZER (2008) suggest in their guideline for avalanche control services in Switzerland a three step approach for assessing and mitigating avalanche risk: (1) data analysis and danger evaluation, (2) assessing the danger to people or infrastructure, (3) decision on preventive measures. The guideline for Tyrolean avalanche control services (RIEDL et al., 2012) is based on a similar concept with the following four steps: (1) risk identification, (2) risk assessment, (3) risk control, (4) review effectiveness. Supplementary standards are given by STIFFLER et al. (2002) for ski areas in Switzerland.

Table 3: Information tools for avalanche control services

	Class I	Class II	Class III	Austria	Switzerland	South Tyrol (I)	Documentation	Description
Webbased information tools								
SPP	x	X			X		X	database with snow profiles
IFKIS	X	x	x		X		X	documentation & exchange platform
LWDKIP				x		X	X	documentation & exchange platform
avalanche bulletin	X	x	X	X	X	X		avalanche bulletin & add. information
weather forecast			X	X	X	X		weather nowcast & forecast
webcams			X					weather nowcast
Computer based information tools								
NXD	x			X	X		X	local avalanche forecasting tools based on previous avalanche data and statistical nearest neighbour methods
AFADE	x			X			X	
ADS	x			X			X	
SNOWPACK		X			X			snowpack simulation model
Manual observations								
study plot		X	x	X	X	X		periodical snowpack and weather obs.
avalanche observations	X			X	X	X		observation of natural avalanches
snow profile	x	X	x	X	X	X		snowpack structure and measurements
shear and (in)stability tests	X	x		X	X	X		CT, ECT, RB, ST, PST, TBT, SFT
loading tests	X			X	X	X		loading tests with ski or explosives
penetrability and probing		X		X	X	X		ram, ski or foot penetr. / ski pole test
Remote observations								
AWS wind station		X		X	X	X		data on wind speed and direction
AWS snow station		x	X	X	X	X		data on snow height, surface temp.
AWS weather station			X	X	X	X		data on temperature, humidity, radiation
precipitation radar			X	X	X	X		regional precipitation
avalanche radar	X			X	X			automatic avalanche observation
Developing tools / scientific tools (wet snow avalanche specific)								
snow fork		X						manual measuring of water content
denoth meter		X						manual measuring of water content
AWS snowpack analyser		X						data on temperature, humidity, moisture
ground penetrating radar		X						moisture content, wetting front
FMCW radar		X						moisture content in upper snowpack
photogrammetry		X						detection of wet snow surface
SMP snow micro-pen		X						measure mechanical snow parameters
peta sonde		X						manual temperature measurements
soil moisture sensor		X						measuring moisture content
lysimeter		X						measuring water outflow

Source: own illustration completed with information from Bartelt and Lehning, 2002; Bründl et al., 2004; Conway et al., 2004; Denoth, 1994; Föhn, 1987; Gassner, 2001; Gauthier and Jamieson, 2007; Höller and Fromm, 2008; Jamieson, 1999; Jamieson, 2004; Kleemayr et al., 2000; Lussi et al., 2012; Marshall et al., 2007; Mayr, 2006; McClung and Schaerer, 2006; Mitterer et al., 2011a; Mitterer et al., 2011b; Mitterer, 2012; Nairz, 2007; Peitzsch et al., 2012a; Pielmeier and Schweizer, 2007; Schaerer, 1988; Sihvola and Tiuri, 1986; Simenhois and Birkeland, 2006; Skoric, 2013; Sommer and Fiel, 2010; Steininger, 2007; Studeregger et al., 2012; Techel et al., 2008; Techel, 2010; Techel and Pielmeier, 2011; Wiesinger et al., 2013; WSL, 2008; WSL, 2012; Wyssen et al., 2012; Zenke, 2009.

A consistent documentation of the whole process is crucial for potential legal procedures, following possible accidents and to keep the knowledge about avalanche situations from the past (STOFFEL and SCHWEIZER, 2008). The iteration of the whole process depends on the weather and avalanche situation - generally, it is done once a day in ski areas and at least during periods of endangerment for roads and settlements. Rapidly changing weather and snow conditions may require more assessment processes during the day.

The evaluation of the local weather and snow situation includes a comprehensive collection of weather, snowpack and avalanche data, followed by a detailed data analysis. According to MCCLUNG and SCHAERER (2006) 'the factors to interpret snow instability may be roughly stratified into three classes, based on their ease of interpretation and relevance for assessing snow instability':

- Class I: Instability factors include current avalanches, loading tests (by skiing, explosives or slope instability tests) or fracture propagation, cracking of the snow cover and settlement noises.
- Class II: Snowpack factors include all information on the current state of the snowpack like, for example, structure, temperature and wetness.
- Class III: Meteorological factors 'provide indirect evidence about current or future snow stability or weaknesses' (MCCLUNG and SCHAERER, 2006).

The following table provides a list of standard information tools available for avalanche control services in Austria, Switzerland and South Tyrol (Italy).
Most of the listed tools are suitable for dry and wet snow conditions. However, there are some exceptions and limitiations concerning wet snow conditions:

- According to a survey of TECHEL (2010), shear and stability tests are only rarely used to forecast wet snow instabilities. In field experiments of TECHEL (2010), the Rutschbock showed a high potential to detect stable and unstable wet snow slopes. ECT and ST do not give significant results. They can only provide additional information in the assessment process. In field experiments of BROWN (2008) during spring melt of snowpacks with basal depth hoar, various tests tend to have low scores or indicate low compressive or shear strength for periods of high wet snow instability (MITTERER, 2012). Results of these studies show that the application of shear and stability tests is possible with limitations to different snowpack structures and stability tests.

- Nearest neighbour programs like NXD, AFADE or ADS are usually adjusted for application in dry snow conditions, therefore, the results in wet snow conditions may be limited.
- Wet snow specific tools for research purposes only are listed in the last part of the table.
- Because of the regional scale and various difficulties in wet snow avalanche prediction (TECHEL, 2010), avalanche bulletins often forecast wet snow avalanche activity even on days with low or no activity (WIESINGER, 2004).

Avalanche forecasting is a process 'of analysing numerous factors acting together in a complicated fashion, recognizing which factors are relevant and determining their relative weights. The analysis involves skills and judgement in applying snowpack physics, empirical relations, experience and the feel of the snow's texture' (McCLUNG and SCHAERER, 2006). Based on multiple information on instability, snowpack and weather data, avalanche control services are forecasting the avalanche danger for a local- or micro-scale. The forecast should include the release probability, the possible size and timing for different avalanche types and avalanche paths (terrain characteristics). The danger rating may differ from the avalanche bulletin (regional forecast) because of the matter of scale. The micro-scale forecast includes the hazard assessment for one or more specific avalanche paths, under consideration of potential damage to people and infrastructure based on the avalanche path characteristics (avalanche map), on the effectiveness of available permanent protection measures and on previous avalanche activity in the path during the winter or the present cycle (STOFFEL and SCHWEIZER, 2008).

There is a principle difference between forecasting for residential areas or roads and the forecasting in ski areas: 'Whereas in ski areas the avalanche return period is on the order of 0.1 to 2 years, it is typically about 1 to 20 years for avalanches reaching the valley bottom and endangering roads or settlements' (STOFFEL and SCHWEIZER, 2008). Hazard assessment for roads and settlements is usually done from the valley bottom. In contrast to the hazard assessment in ski areas, valuable class I instability information and personal observations at elevations and aspects of starting zones are often not available (STOFFEL and SCHWEIZER, 2008).

'Based on the estimated probability and size of an avalanche in the path under consideration a decision needs to be taken on whether preventive measures are necessary' (STOFFEL and SCHWEIZER, 2008) or not, or whether previously taken measures can be cancelled. Possible preventive measures do have short-term character (MARGRETH and BURKARD, 2010) like, for example, evacuation, closure or artificial avalanche release.

The preparation of control operations includes the choice of the release points, the choice of artificial release methods, the preparation of the explosives and the closure of endangered areas (INNERKOFLER, 1999). If artificial avalanche release is conducted in many avalanche paths at once, a detailed operation plan including the sequence of release points is required to enable a safe and efficient control operation (STOFFEL, 2001). In wet and dry snow conditions the timing of control operations is crucial. With regard to high success rates, the best timing is generally 'as fast as possible for dry snow avalanches and as late as justifiable for wet snow avalanches' (MAIER, 2008). The release success is continuously evaluated during control operations. A positive release success is defined as a significant avalanche release with regard to the size of the starting zone (STOFFEL, 2001). Within ski areas small starting zones just above ski runs are common, therefore, sluffs or small avalanches are already rated as a positive release success, whereas a sluff in a huge starting zone above a road is generally rated negative. Results are documented for each triggered release point. A reassessment of the avalanche hazard is required after the control operation to decide whether closed areas can be reopened or not. Reopening is usually considered more difficult than initial closing.

4 Questionnaire-based survey

4.1 Introduction

Chapters 2 and 3 introduced the theoretical concepts for wet snow avalanches and artificial avalanche release. Very limited research work exists on the applicability of artificial avalanche release in wet snow conditions, beause it has been considered as not feasible (SCHWEIZER, 2007; STOFFEL, 2001). Nevertheless, in recent years, avalanche control services have increasingly released wet snow avalanches by explosives (SCHWEIZER, 2007; MARIENTHAL et al., 2012; STOFFEL, 2013).

The objective of the survey is to collect experience and knowledge of practitioners and to provide statistical data. Therefore, avalanche control services in Austria, Switzerland and South Tyrol (Italy) were approached with a questionnaire concerning the application and their experience with artificial release of wet snow avalanches. The research questions are presented in the following list.

Research questions:

Where and under which weather situations are wet snow avalanches frequently artificially released? What is the best timing for control operations?

Which release methods are used for wet snow avalanches? Are different release methods especially suitable for wet snow avalanches?

How effective is the artificial release of wet snow avalanches and is it possible to significantly reduce closure times?

What is the relevance of artificial release of wet snow avalanches compared to dry snow avalanches?

The intention of the survey is to assess the current state of artificial release of wet snow avalanches in ski areas and above highways / roads. The results are linked to the theoretical concepts and precised through the following-up expert interviews.

Therefore, the survey helps to find out best practice examples for expert selection and to define further research questions and hypotheses.

Some of the results have been presented in conference papers and posters (OBERHAMMER and SCHWEIZER, 2008; WIESINGER et al., 2013).

4.2 Methods

4.2.1 The questionnaire

A questionnaire, consisting of 38 questions, was designed and pretested. The structure of the questions is either open, semi-closed or closed (PORST, 2011). The questionnaire was prepared in German and French language. The German version of the questionnaire is attached in appendix A. The questions are grouped into 7 categories.

(1) General information: The first category with 3 questions intends to get an overview of the respective avalanche control service.

(2) Characterization of the terrain: The second category consists of 7 questions and helps to characterize the terrain in which the avalanche control service is operating. Questions are structured as closed questions (4) and open questions (3).

(3) Snowpack and weather: This category is focusing on the assessment of wet snow stability, information sources and weather conditions leading to control operations. The category consists of 5 closed questions, 2 semi-closed questions and an open question at the end for supplementary information.

(4) Timing of control operations: This category includes 2 semi-closed questions on the timing of control operations during different weather conditions and 1 open question for supplementary information.

(5) Artificial release: Control operations and release methods are the focus of 9 questions in this category. Questions are structured as closed (5), semi-closed (2) and open questions (2).

(6) Release success rate: This category includes 6 closed and 1 semi-closed questions on release success and related topics.

(7) Special experiences: The last category includes an open question which encourages further input.

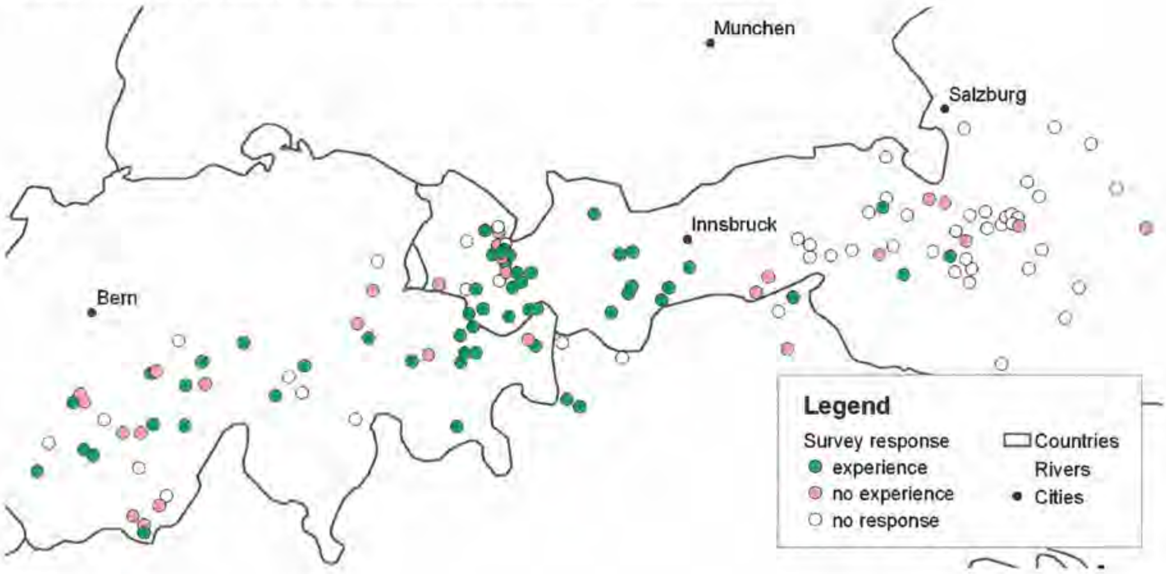
The questionnaire was distributed by mail. Contact lists and addresses of the Swiss avalanche control services were obtained from the SLF. For the avalanche control services in Austria and South Tyrol (Italy) addresses were gained through an internet research and through the support of regional avalanche forecasters. Altogether 112 questionnaires were mailed to avalanche control services. For the Tyrolean avalanche control services an online survey was conducted on the online platform LWDKIP (ZENKE, 2009) with support from the Tyrolean avalanche forecasting service. A cover letter with recommendations of the regional responsible avalanche forecasters was enclosed in order to increase the return rate.

4.2.2 Data

The survey was done in spring 2008. A total of 50 completed questionnaires were returned by experienced avalanche control services, another 28 avalanche control services reported that they do not have any experience with artificial release of wet snow avalanches. This equals an average return rate of about 54%. The return rate for Tyrol cannot be calculated because of the online survey. The detailed return rate for different countries and regions is shown in figure 18. The geographical distribution is shown in figure 12.

Most of the respondents are responsible for avalanche safety in ski areas (47), some of them (18) additionally operate in the avalanche safety service of the related community (for example road networks, cross-country ski runs). Only few respondents are exclusively responsible for the avalanche safety of highways and pass roads (3).

Figure 12: Geographical distribution of returned questionnaires



4.2.3 Data analysis

Descriptive statistics were used to analyse closed and semi-closed questions:

a. Questions with dichotomous answer possibilities (7) were analysed by counting the 'yes' or 'no' answers. Calculated percentages are presented.

b. Questions with ordinal answer possibilties (13) were analysed through contingency tables. Results are presented as bar plots. Additionally, index sums were calculated in order to compare grouped answers. To calculate the index sum, answers were weighted according to their ranks. Possible answers and their assigned weights (in brackets) are:

- often (1) - sometimes (0,66) - rarely (0,33) - never / not avaiable / no answer (0)
- many (1) - multiple (0,66) - several (0,33) - no / no answer (0)
- important (1) - slightly important (0,5) - not important (0) - not available / no experience / no answer (0)

c. Questions with numerical answer possiblities (2) were analysed through contingency tables. Results are presented in bar plots. Additionally, mean values and sums were calculated and presented.

d. Questions with nominal answer possibilities (6) were analysed through contingency tables. Results are presented in bar plots.

Open questions were analysed qualitatively or with descriptive statistics:

a. Open questions with numerical answers (3) were analysed with box plots.

b. Comments on open questions (5) and additional comments on semi-closed questions were qualitatively analysed. Information given by the respondents were structured and summarized.

c. Questions on name and contact data (2) were used to generate geographical illustrations.

Because of the small sample sizes, the Fisher exact test was used to analyse contingency tables of binary, nominal and ordinal data (RASCH et al., 2010a). Rank-based statistics were used to compare two (Mann-Withney-U test) or more than two (Kruskal-Wallis-H test) groups of ordinal or metric data (RASCH et al., 2010b).

Multiple test and group variables have been created out of the survey results. The variables have been comprehensively tested with regard to their association. Significant results are mentioned and discussed in the following chapters. Significant associations may be identified by several tests: The highest p-values tested are shown in brackets. A list of all significant test results is shown in appendix A.

Microsoft Excel and statistical software SPSS were used to analyse data and to create charts. The geographical information system ESRI ArcGis was used to create geographical illustrations.

4.3 Results

4.3.1 Release zones and terrain characteristics

A general overview of the geographical distribution of the survey and respondents is given in figure 12. The survey is focusing on avalanche control services in the northern and central Alps of Switzerland and Austria including South Tyrol (Italy).

Release zones are generally located above 1500 m sealevel. There are no responses on release zones with lower altitude. Most of the respondents (N=50) artificially release wet snow avalanches in release zones between 2000 m and 2500 m (70%). Release zones between 1500 m and 2000 m (44%) as well as release zones above 2500 m (42%) are also common.

Most of the respondents are dealing with southerly (SW - SE) exposed release zones (78%). However, about 60% of the respondents do also control wet snow avalanches in northerly (NE - NW) exposed release zones. Details on the aspect of the release zones are shown in figure 19. There is a remarkable difference between easterly (50%) and westerly (38%) exposed release zones.

Release zones with a slope angle of between 35° and 40° are most common: Nearly 80% of the respondents do have at least multiple release areas in this slope angle category. Release zones with flatter or steeper slope angles are less frequent. Details are shown in figure 20. The terrain among the release zones varies: More than 50% of the respondents do have at least multiple release zones with rock, gramineous or scree slope. Only release zones with dwarf-shrub vegetation are less frequent. For more details see figure 20.

The number of release points characterizes the size and the exposure to avalanches of a given operating area (figures 13, 14). On average, the respondents do have 87 release points for dry snow avalanches. Overall, about one third of the release points is also prone to wet snow avalanches. In some areas almost all release points are prone to wet snow avalanches (figure 15). The respondents control between 2 (minimum) and 379 (maximum) release points for wet snow avalanches in their operating area. Details are shown in figures 13 to 17 and figure 21.

Those avalanche control services with release zones in southerly exposed slopes (SE, S, SW) do have more wet snow avalanche release points ($p \leq 0,05$). The number of control operations is higher ($p \leq 0,01$) - especially in March ($p \leq 0,05$). They observe significantly less remote wet slab avalanches ($p \leq 0,01$). Rain on snow events are more frequent ($p \leq 0,05$). Metereological factors are rated more important for wet snow instability forecasting ($p \leq 0,05$).

Gramineous slopes are more frequently in southern slopes ($p \leq 0,05$) than in other aspects. Slopes with dwarf-shrub vegetation are most common in lower elevations ($p \leq 0,05$). Low elevations are also more prone to rain on snow events ($p \leq 0,05$).

In areas above 2500 m southern release zones are less frequent ($p \leq 0,05$) than in lower areas. Release areas above 2500 m are generally less inclined than release zones in lower elevations ($p \leq 0,05$).

Respondents with release zones below 2000 m generally have fewer release points for dry ($p \leq 0,05$) and wet snow avalanches ($p \leq 0,01$). Ski slopes in ski areas below 2000 m seem to be less endangered by dry snow avalanches ($p \leq 0,05$). Control operations often start in February in areas below 2000 m ($p \leq 0,05$), whereas control operations for wet snow avalanches are an exception in areas above 2500 m in February ($p \leq 0,001$) and March ($p \leq 0,05$). Control operations in May are exclusively carried out in release zones above 2000 m ($p \leq 0,05$).

As rocky starting zones are steeper, avalanche control services with many rocky starting zones generally operate in steeper control areas ($p \leq 0,05$). Those who have a lot of gramineous slopes mainly have release zones between 35° and 40° ($p \leq 0,001$).

Figure 13: Avalanche control services and release points for wet snow avalanches

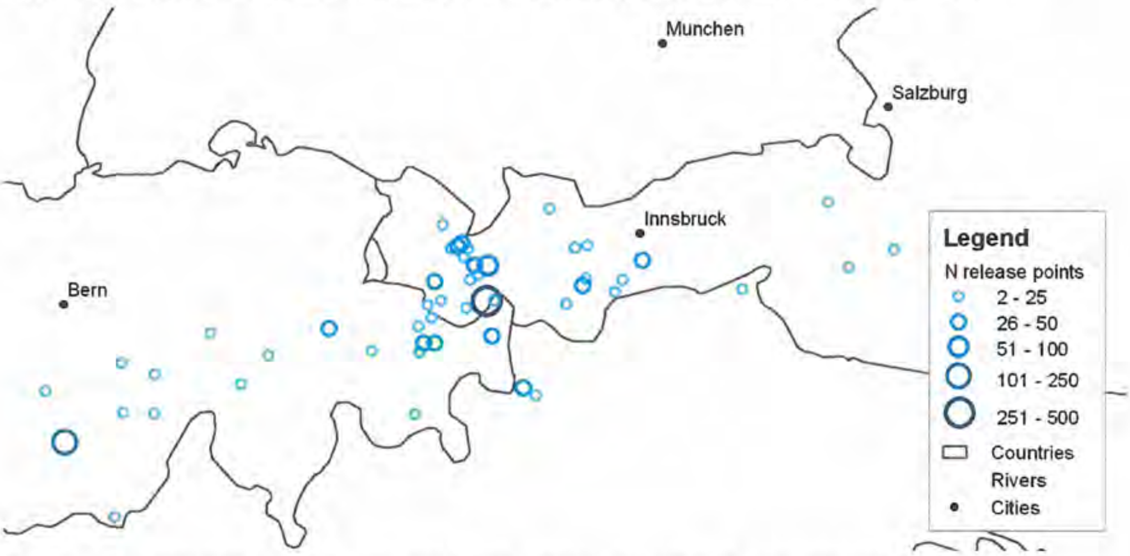


Figure 14: Avalanche control services and release points for dry snow avalanches

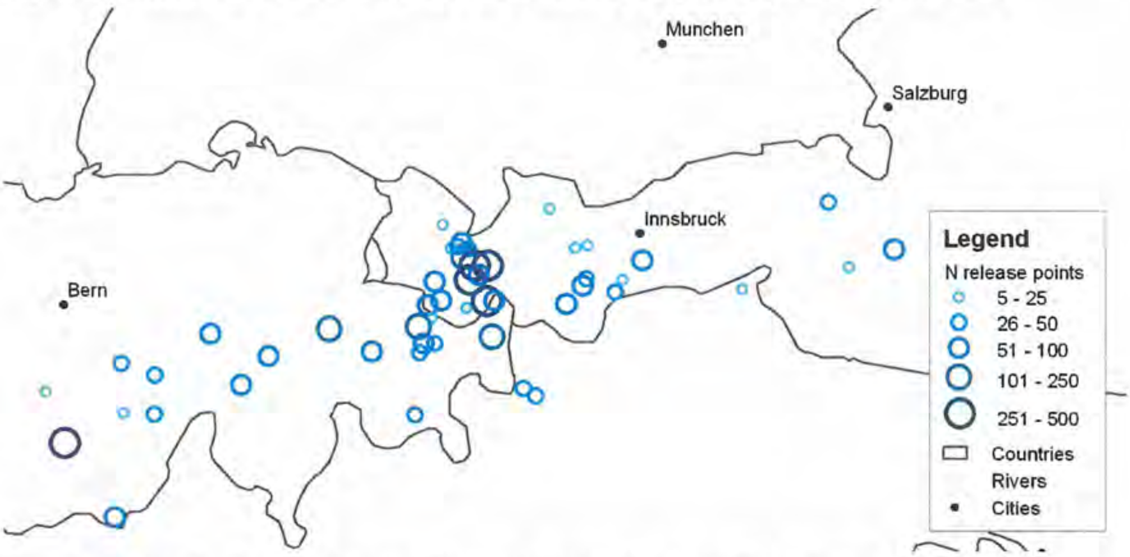


Figure 15: Proportion of wet snow avalanche release points to dry snow release points

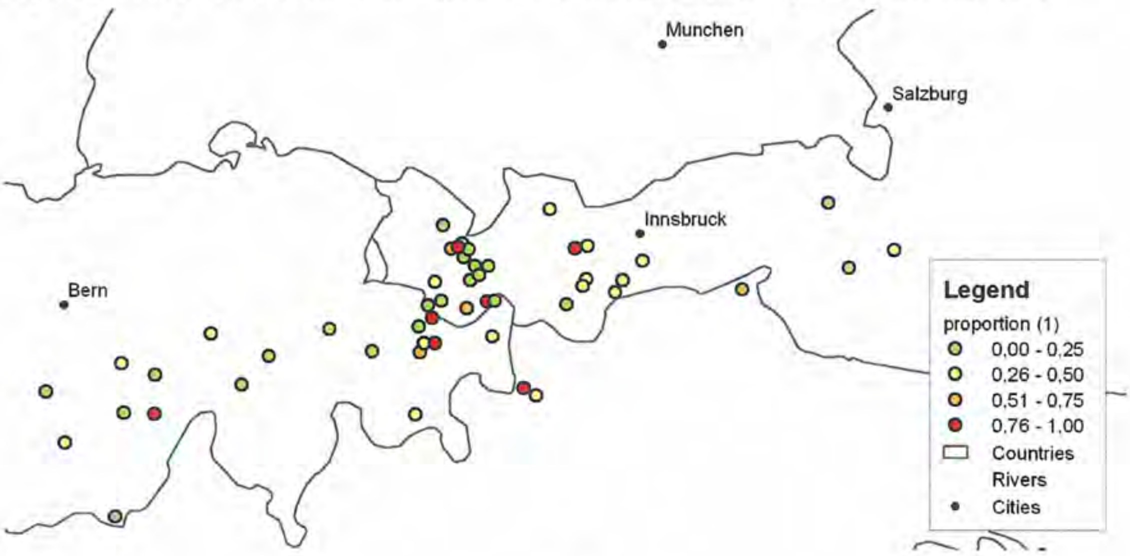


Figure 16: Avalanche control services and release points per kilometer of ski slopes

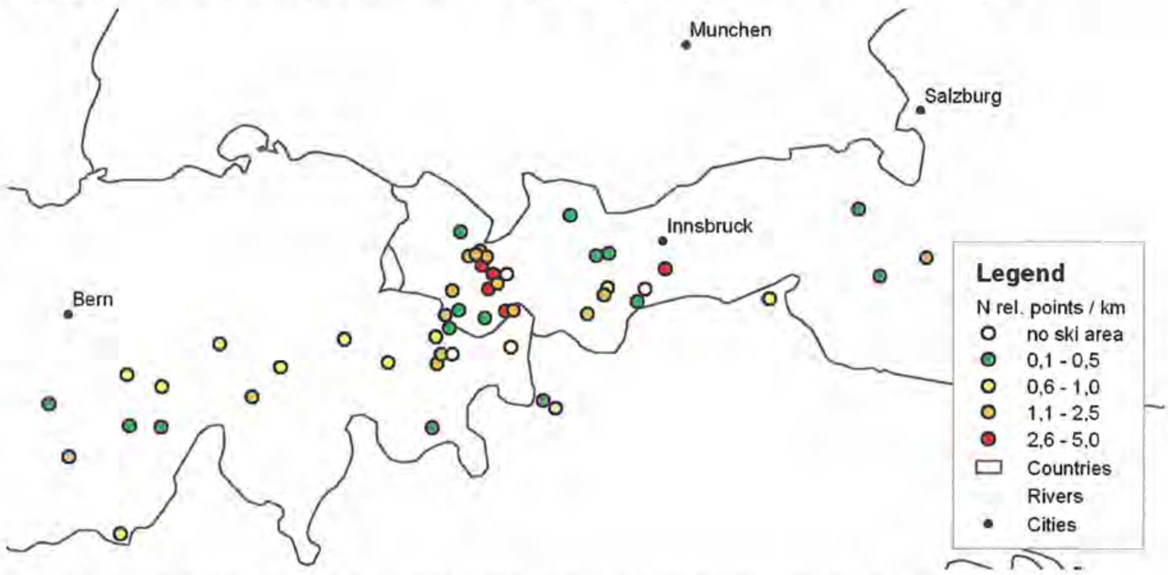


Figure 17: Avalanche control services and release points per kilometer of roads

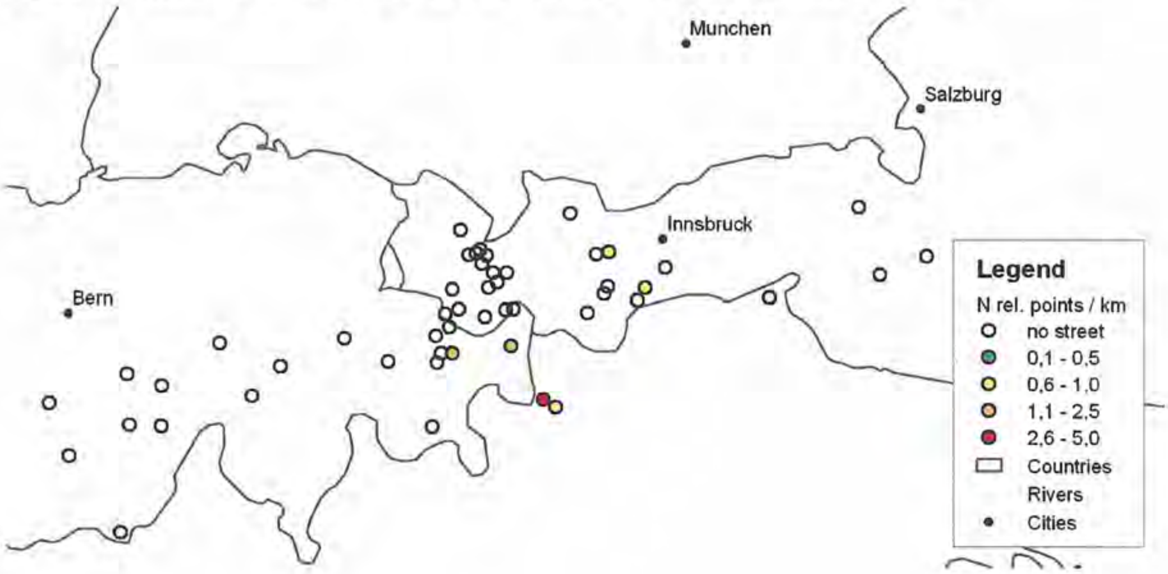


Figure 18: Survey and return rates (shown in brackets)

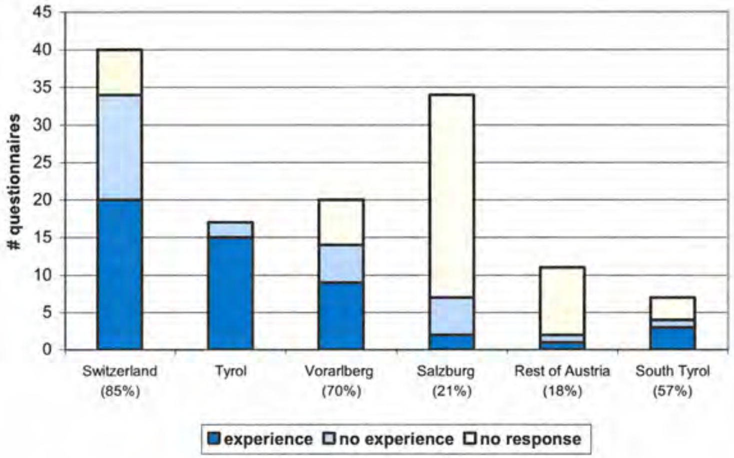


Figure 20: Slope and terrain of release areas (N=50)

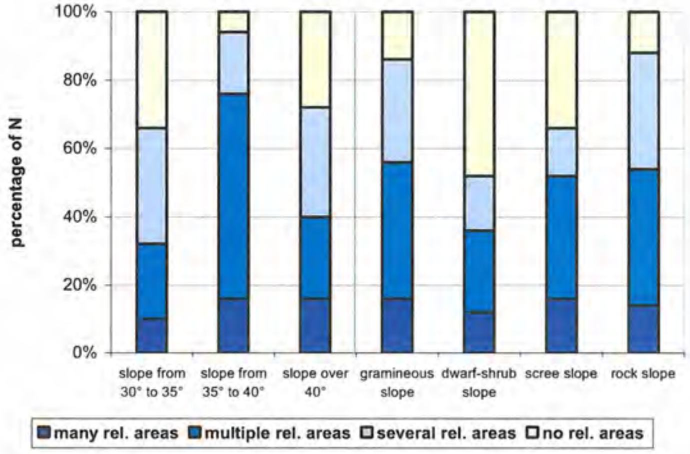


Figure 19: Aspect of release areas (N=50)

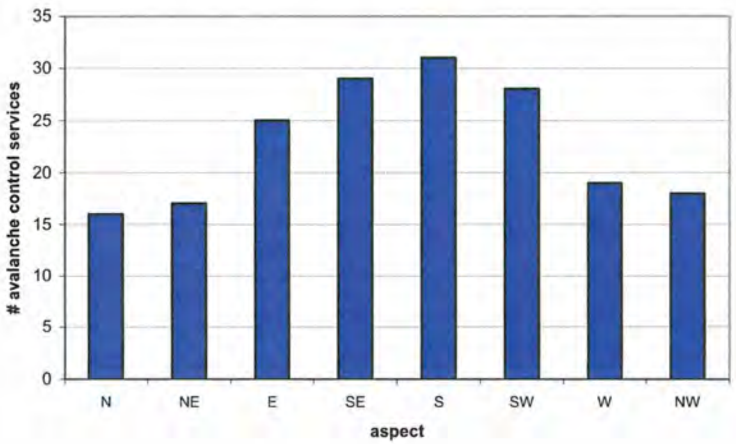
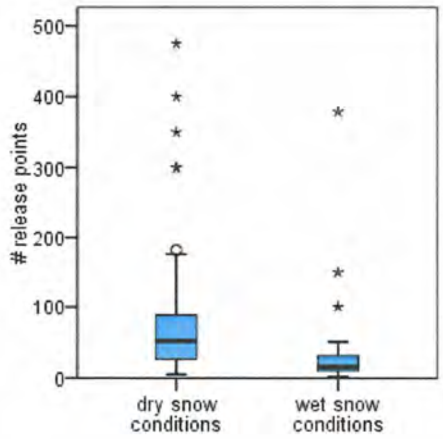


Figure 21: Release points for dry and wet snow avalanches (N=50)



4.3.2 Weather situations and timing of control operation

Almost all avalanche control services try to release wet snow avalanches during warm spring periods. Nearly 60% of the respondents often conduct control operations during such weather situations. Rain on snow events also seem to be a common problem. About 70% of the respondents state that, at least sometimes, rain on snow events are leading to control operations. Wet snowfall and rapid warming after snowfall are less frequent triggers for control operations. Details are shown in figures 22 to 24 and figure 35.

In November, December and January control operations for wet snow avalanches are an exception. First control operations are generally conducted in February. Peak time for control operations is in April: The participating avalanche control services are running over 200 control operations in this month, on average more than 4 control operations each. Almost as many operations are conducted in March with nearly 180 control operations. In May and June control operations are mainly done for the opening of alpine pass roads and in glacier ski areas. Details are shown in figures 25 and 26.

The most important information sources to determine the timing for control operations are spontaneous avalanches, snowpack observations and automatic weather stations. Avalanche bulletin and test releases are also widely used to assess wet snow instability, whereas study plots and NXD programs are less frequently used. For details see figures 27 and 28.

According to the survey, the most important weather parameters to assess wet snow instabilities are radiation, maximum air temperature and amount of rain (figures 29 and 30). Penetration depth, snowpack layering and basement are considered the most important snowpack characteristics (figures 31 and 32). Some respondents do have rules to assess wet snow instabilities during warm spring periods within their operating area. Temperature based rules (8) are most common. Altitude of freezing level and threshold values for minimum and maximum temperatures are the basis of those rules. The rules mentioned are specific for each region. Therefore, they are not listed in detail. Other rules mentioned indicate wet snow instabilities during warm spring periods when ...

- ... relative humidity reaches values of above 60% (1).
- ... at least 2/3 of the snowpack becomes isothermal (1).
- ... the snowpack becomes completely isothermal (2).

Many respondents additionally mentioned that several weather and snowpack parameters are necessary to forecast wet snow avalanche activity (14). A good indicator may be the shining surface of wet snowpacks (1). Another respondent noted that information on the snowpack basement is important to forecast wet snow avalanches in northerly exposed slopes (1). The spring warming from the bottom of the snowpack is mentioned by other respondents (3). Foehn was also mentioned as a common trigger for wet snow instabilities (3). The depth of the snowpack in the release area defines the wet snow avalanche potential and is, therefore, an essential snowpack parameter in forecasting wet snow avalanches (1). Among others, the depth of the snowpack in the starting zones is also influenced by the frequency and size of released dry snow avalanches (1). One respondent additionally noted that foggy weather conditions with intense radiation during warm spring periods often lead to wet snow instabilities (1).

Most avalanche control services (66%) agree that control operations in warm spring conditions are most effective after several hours of solar radiation (figure 33). Some respondents (4) additionally mentioned that the best moment is just before sunset. However, many avalanche control services (48%) expect the best moment for control operations just after the last sundown (figure 33). A refreezing crust on the snowpack surface is leading to a better fracture propagation (1). Rapid warming and radiation after (wet) new snow are immediately leading to wet snow instabilities - therefore, the control operations should start right after warming and radiation have started (1).

Control operations in rain on snow conditions seem to be most effective after several hours of rain (48%) or after the rain (46%). In weak snowpacks avalanche activity often starts directly after the onset of rain (2). Details are shown in figure 34.

Those avalanche control services who often release wet snow avalanches during warm periods use class I and class II information sources more frequently. Warm periods are the most frequent trigger for wet snow avalanches. During warm periods the biggest amount of explosives ($p \leq 0,01$) is used and most control operations ($p \leq 0,05$) are conducted especially in April ($p \leq 0,05$).

Respondents who are controlling southerly exposed release areas rate class III information as more important - especially weather stations ($p \leq 0,05$). Those avalanche control services who operate with northern release zones rate snowpack temperature as more important ($p \leq 0,05$).

Control operations in February are frequently related to rain on snow events ($p \leq 0,05$). Rain is not a common trigger for wet snow instabilities above 2500 m ($p \leq 0,01$). Those avalanche control services who operate above 2500 m rate information on snowpack basement ($p \leq 0,05$), rain ($p \leq 0,01$), cloudiness ($p \leq 0,05$), penetration depth ($p \leq 0,05$) and class I factors ($p \leq 0,05$) as less important. However, rain on snow events are less frequently observed by those avalanche control services who operate in westerly release zones ($p \leq 0,05$).

Figure 22: Avalanche control services and control operations during warm spring periods

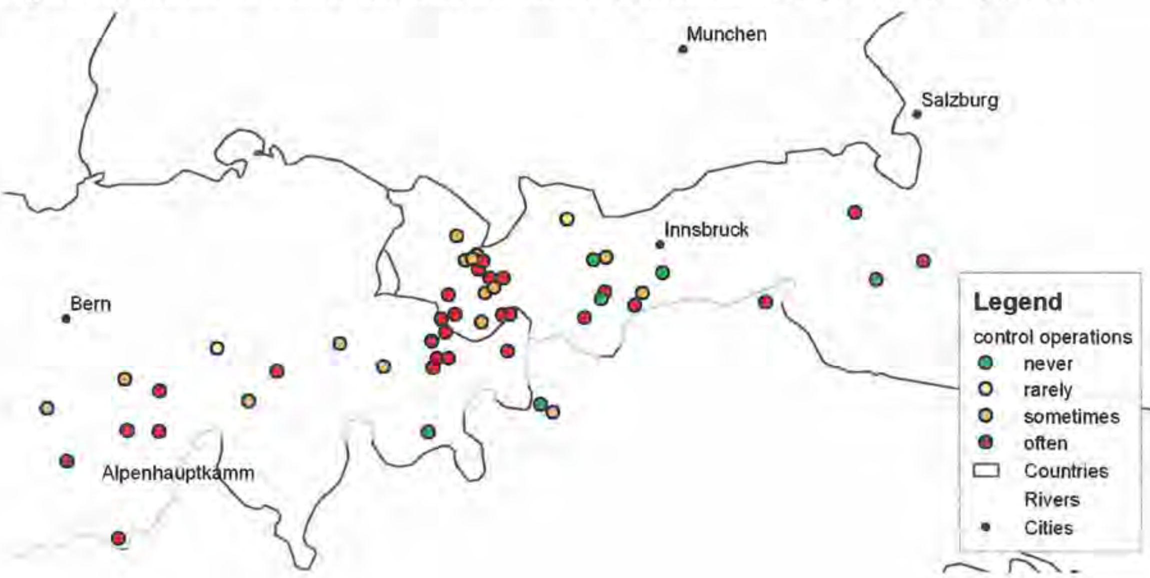


Figure 23: Weather situations leading to control operations (N=50)

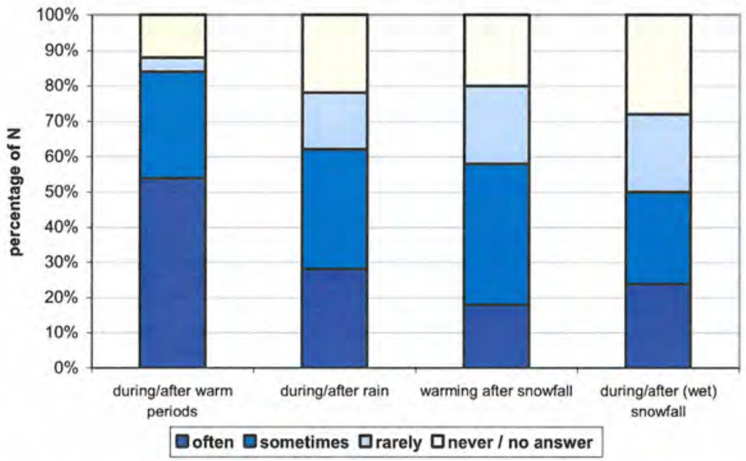


Figure 24: Index sum of weather situations leading to control operations

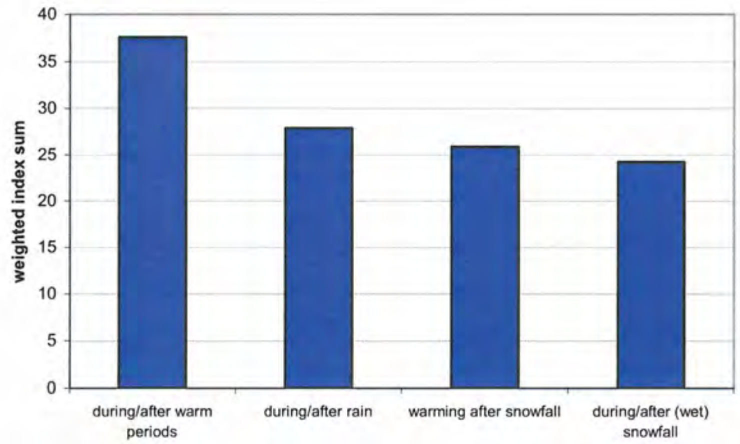


Figure 25: Control operations between November and June (N=50)

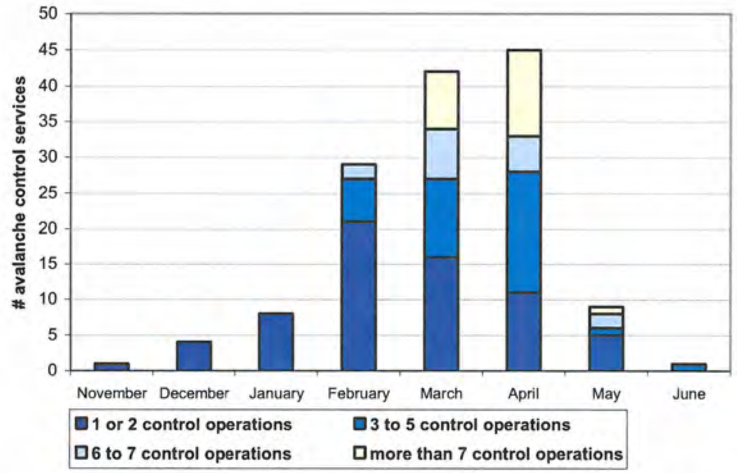


Figure 26: Number of control operations between November and June

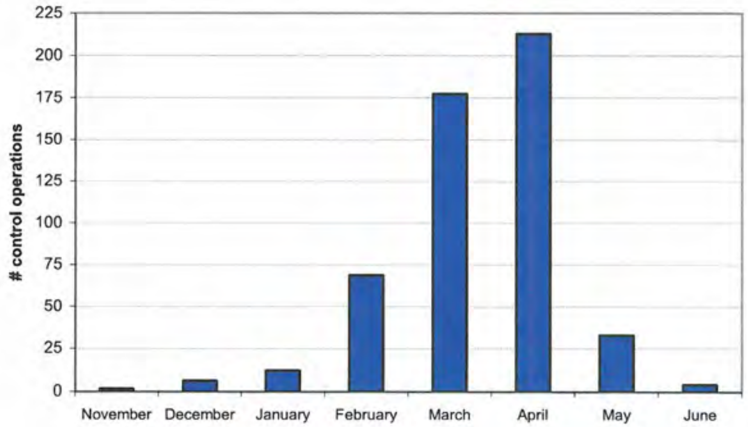


Figure 27: Importance of information sources (N=50)

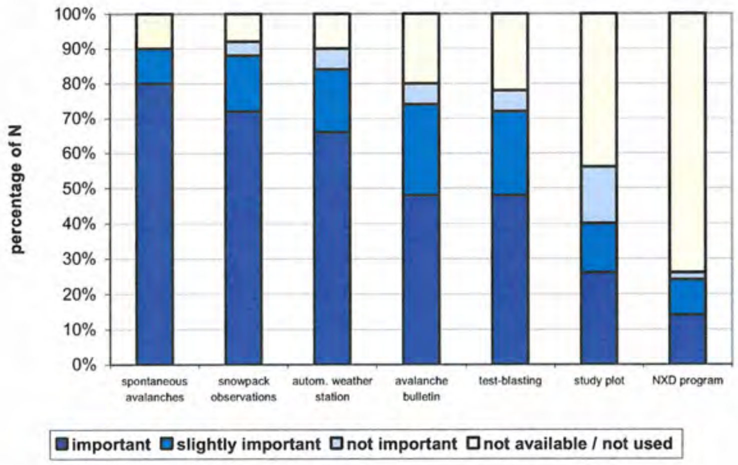


Figure 28: Weighted index sum of information sources

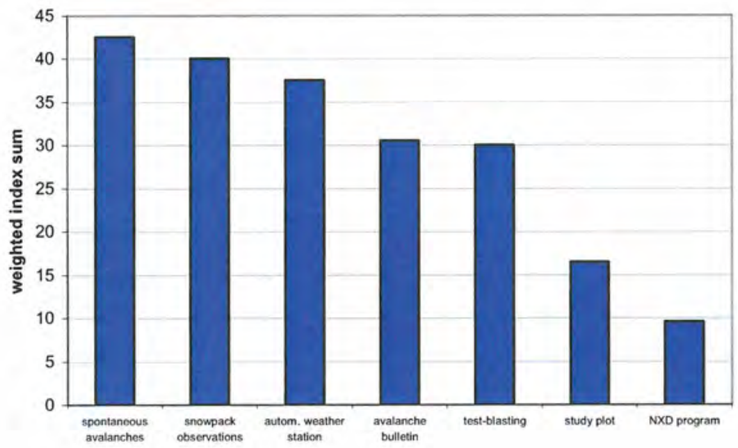


Figure 29: Importance of weather parameters (N=50)

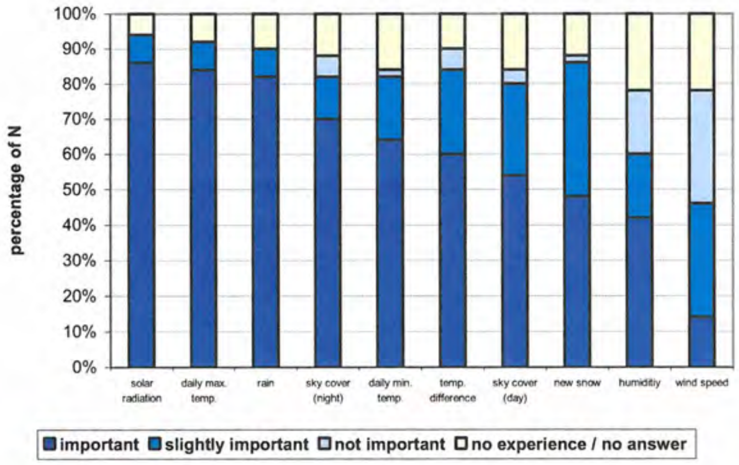


Figure 30: Weighted index sum of weather parameters

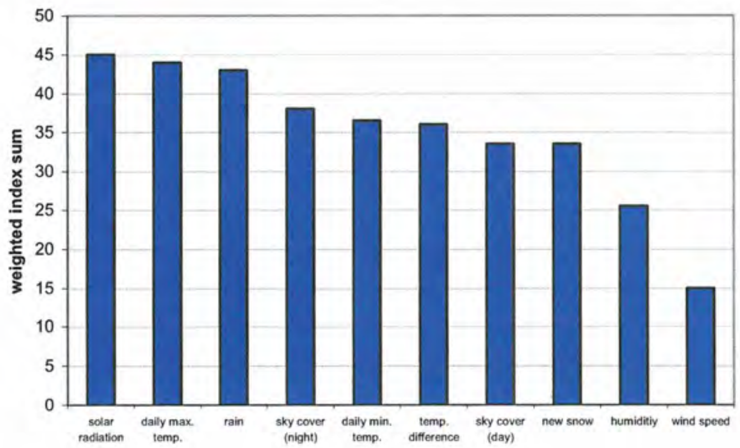


Figure 31: Importance of snowpack parameters (N=50)

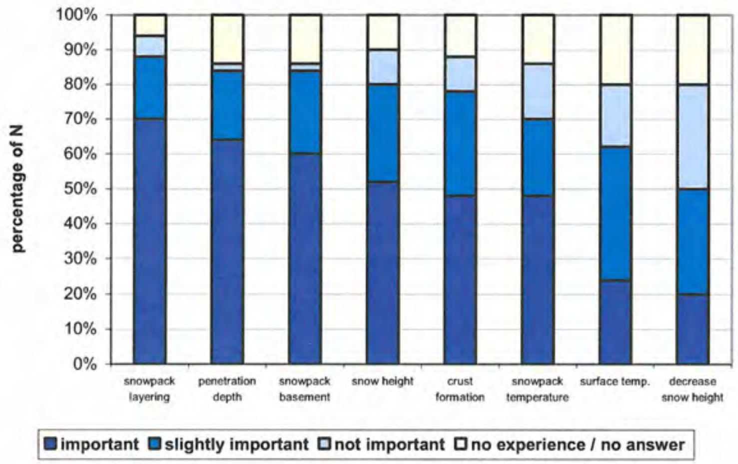


Figure 32: Weighted index sum of snowpack parameters

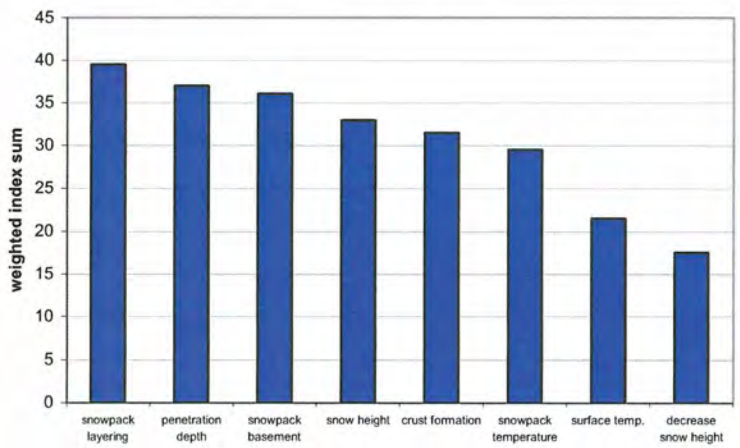


Figure 33: Timing of control operations in spring conditions (N=50)

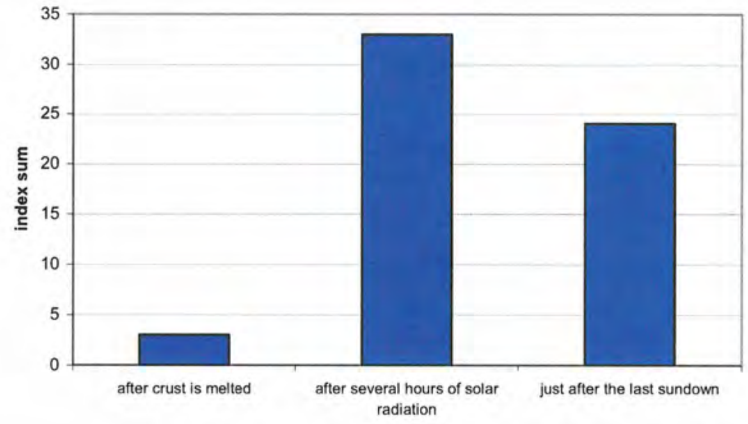


Figure 34: Timing of control operations during rain on snow events (N=50)

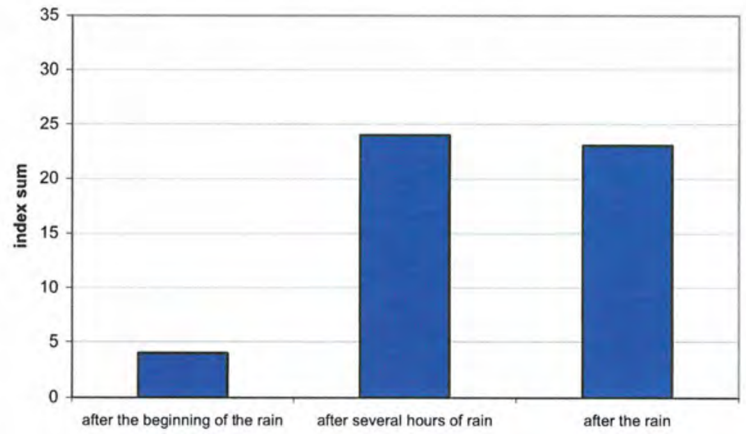
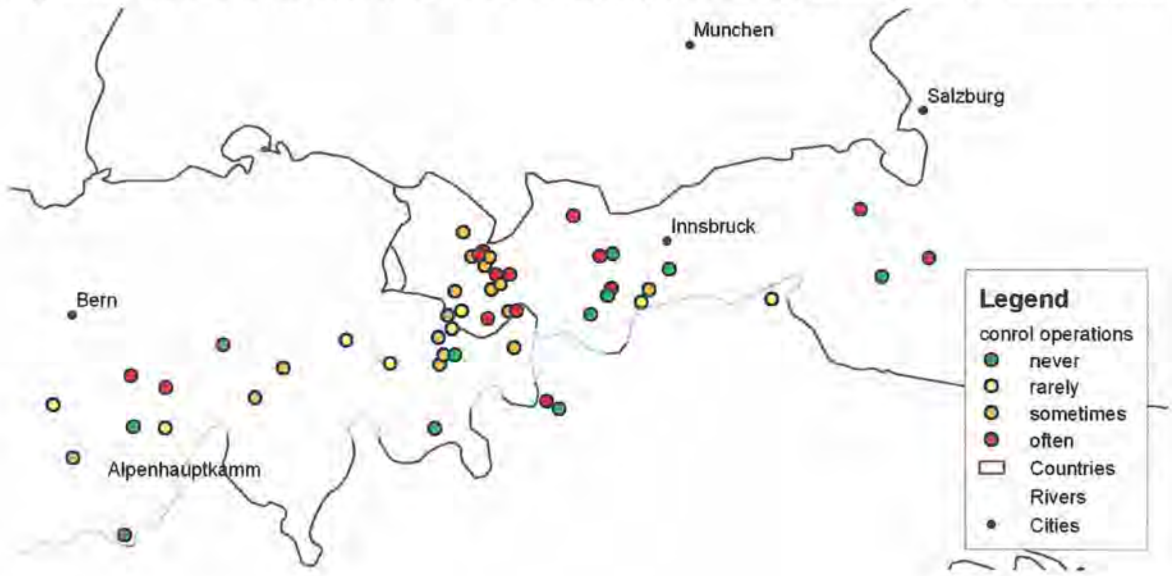


Figure 35: Avalanche control services and control operations triggered by rain on snow events



4.3.3 Release methods and amount of explosives

Charge placement in control operations for wet snow avalanches is mostly done from helicopters or by hand. Ski cutting is also often applied to release wet snow avalanches. Nearly 90% of the responding avalanche control services use, at least sometimes, one of these methods to release wet snow avalanches. Details are shown in figures 36 and 37.

Compared to the artificial release of dry snow avalanches, especially hand and helicopter delivery of explosives and mechanical triggers such as ski cutting and groomers are more frequently used to release wet snow avalanches (figure 40). Projectile devices and towers are less frequently used to control wet snow avalanches. Release methods with flexible charge placement are more frequently used, whereas autonomous devices seem to be less important. According to one third (36%) of the respondents, there is no especially suitable release method for wet snow conditions. Other respondents expect that hand charging (18%) and ski cutting (12%) are especially suitable in wet snow conditions.

About 44% of the avalanche safety teams use bigger charges to release wet snow avalanches than they use in dry snow conditions. Only one respondent uses smaller charges to release wet snow avalanches. One respondent additionally mentioned that the timing is more important than the charge size. Most of the respondents expect to have the best impact in wet snow conditions when charges are placed on or above the snowpack - no matter if they try to trigger wet loose snow or wet slab avalanches. However, there are also avalanche control services who consider charge placement above the snowpack as not suitable in wet snow conditions (2). For details see figure 42. One respondent recommends to place charges within areas of low snow height to release wet loose snow avalanches because there the snowpack is usually completely wet.

On average, the responding avalanche control services (N=43) use about 230 kg of explosives per season to control wet snow avalanches. Details for Gazex and projectile devices are given in table 4. Whereas some avalanche control services apply only a little amount of explosives, there are also some respondents who dissipate up to 1,2 tons of explosives per season to control wet snow avalanches. Details are shown in figure 43. On average, about 13% of the total amount of explosives is used to control wet snow avalanches. However, the portion used for wet snow avalanches reaches values of nearly 40% in some areas (figure 44). The amount of explosives used to control wet snow avalanches is more or less constant in most of the areas (80%). A few avalanche control services (10%) reported an increasing consumption of explosives to control wet snow avalanches due to bigger charges (1) or an increasing number of control operations (3).

The total amount of explosives is related to the total number of release points ($p \leq 0,001$). Generally, bigger ski areas use more explosives ($p \leq 0,05$). Those which use more than 2 tons of explosives per year do apply significantly more explosives per release point ($p \leq 0,05$) - this means that they conduct more control operations during the winter and/or use bigger charge sizes. Compared to those with a total amount of less than 2 tons per year, they use significantly more projectile devices ($p \leq 0,001$), ropeway carriers ($p \leq 0,01$) and hand delivery ($p \leq 0,05$).

The total amount of explosives is also related to the amount of explosives used in wet snow conditions ($p \leq 0,05$). Nevertheless, the relative portion of explosives used in wet snow conditions is generally lower for those who use more than 2 tons in total ($p \leq 0,05$). Avalanche control services who use more than 200 kg of explosives in wet snow conditions dissipate a greater amount of explosives per release point ($p \leq 0,01$) - possibly because they use bigger charge sizes or they conduct more control operations in the same release areas. However, they use more autonomous devices ($p \leq 0,01$) for wet snow avalanche release. Helicopters are used more frequently for artificial avalanche release in ski areas above 2000 m ($p \leq 0,05$).

Opinions differ with regard to the best charge placement. Those who prefer charge placement on the snowpack conduct more control operations in wet snow conditions ($p \leq 0,05$) and they have a bigger area of control ($p \leq 0,05$). Those avalanche control services who use bigger charges also tend to prefer charge placement on or above the snowpack ($p \leq 0,05$).

Those who prefer charge placement in the snowpack to release wet loose snow avalanches use more projectile devices ($p \leq 0,05$). Those who prefer charge placement on the snowpack use more autonomous devices and hand delivery ($p \leq 0,05$).

Respondents operating mainly in southern release areas tend to use the same charge sizes for wet and dry snow avalanches ($p \leq 0,05$). Respondents with northerly release zones prefer charge placement above the snowpack ($p \leq 0,01$).

Table 4: Amount of explosives

	Switzerland			Austria			Others			Total		
	N	Σ	Ø	N	Σ	Ø	N	Σ	Ø	N	Σ	Ø
Explosives												
amount in kg (total)	20	49140	2457	24	41300	1721	2	800	400	46	91240	1983
amount in kg (wet snow cond.)	19	4087	215	22	5535	252	2	200	100	43	9822	228
Gazex												
shoots (total)	3	365	122	10	1480	148				13	1845	142
shoots (wet snow conditions)	2	36	18	10	103	10				12	139	12
Projectile devices												
shoots (total)	11	596	54							11	596	54
shoots (wet snow conditions)	4	85	21							4	85	21

Figure 36: Release methods in use for wet snow avalanches (N=50)

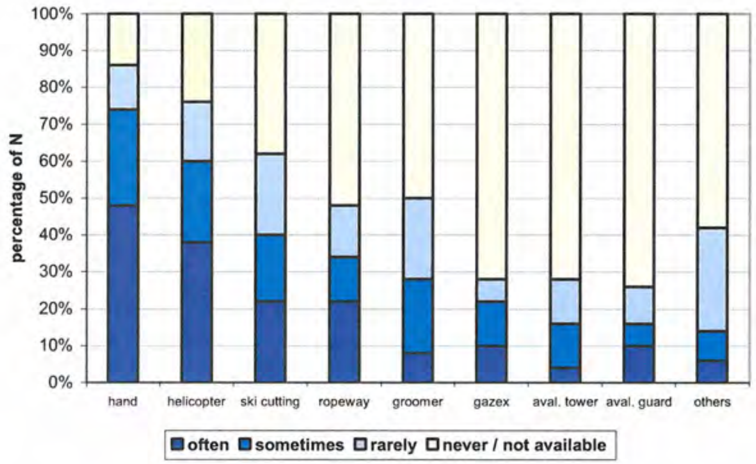


Figure 38: Release methods in use for dry snow avalanches (N=50)

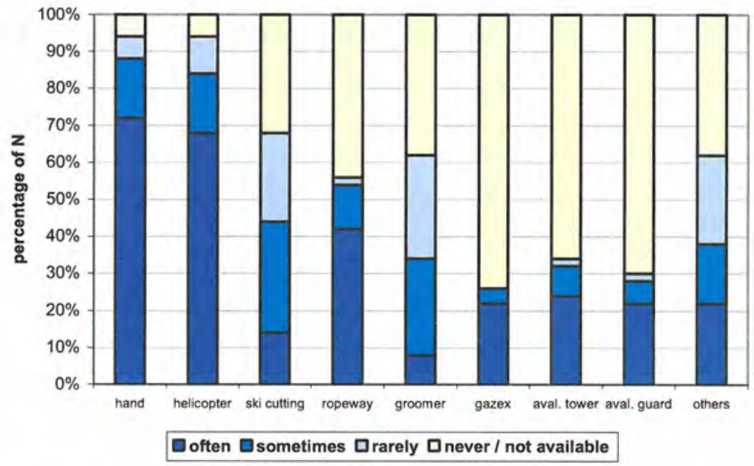


Figure 37: Index sum of release methods in use for wet snow avalanches

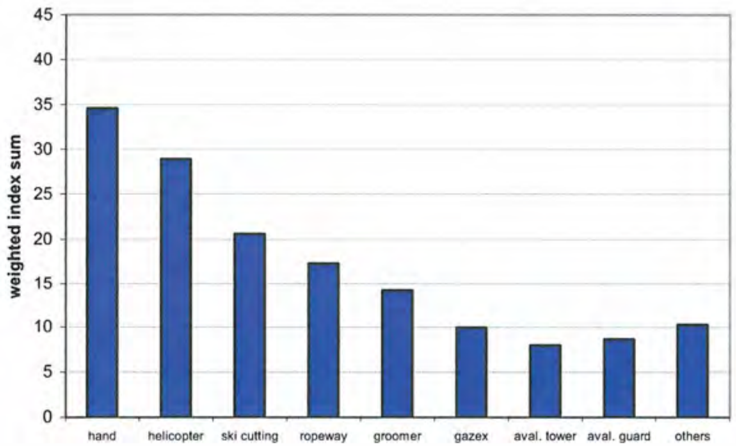


Figure 39: Index sum of release methods in use for dry snow avalanches

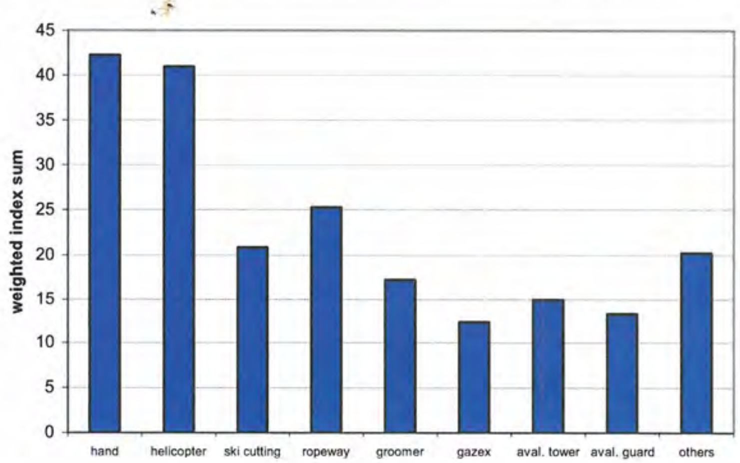


Figure 40: Percentage of index sum per release method and avalanche type

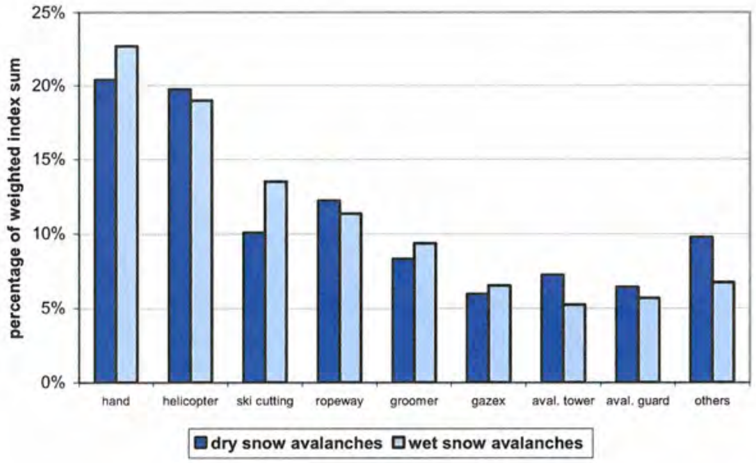


Figure 42: Best charge placement in wet snow conditions (N=50)

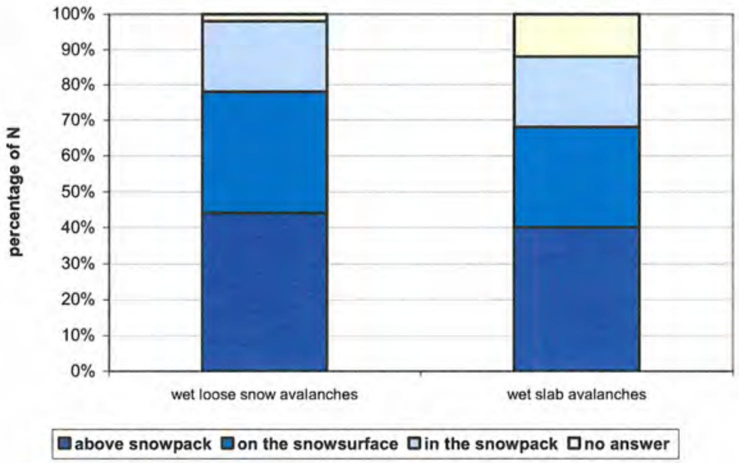


Figure 41: Best release method for wet snow avalanches (N=50)

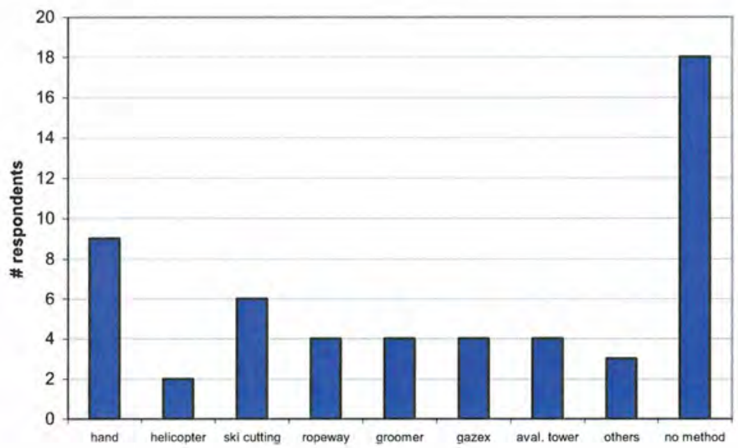


Figure 43: Amount of explosives per season

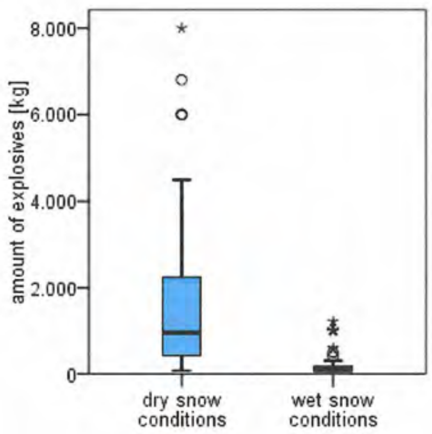
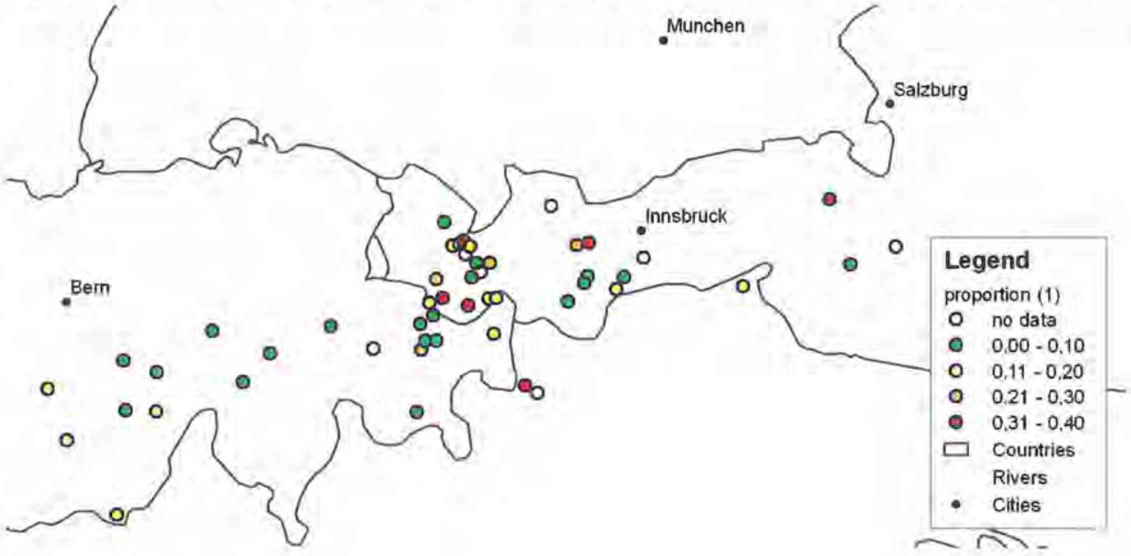


Figure 44: Proportion of explosives used to control wet snow avalanches on total explosive amount



4.3.4 Type and size of released wet snow avalanches

Accoring to the survey wet loose snow avalanches are more frequently triggered than wet slab avalanches (figures 47 and 48). More than half the respondents release, at least sometimes, wet loose snow avalanches within their operating area. About 40% of the respondents sometimes or often release wet slab avalanches.

Avalanches propagate within the snowpack (surface layer avalanches) or as full depth avalanches. The triggered avalanches are sluffs (<100 m^3), small (<1.000 m^3) or medium (<10.000 m^3) sized avalanches. Only 4 avalanche control services trigger many or multiple large avalanches every season. Details are shown in figures 47 to 50.

Secondary releases are quite often observed by the respondents: About 40% of the respondents observed, at least sometimes, secondary releases of wet loose snow avalanches. About 30% of the respondents observed some secondary wet slab avalanches. One respondent noted that small triggered loose snow avalanches can sometimes develop into quite large avalanches through secondary release. Remote triggering seems to be less common: Only 14% of the respondents observed some remote triggered wet snow avalanches associated to their control operations. Details are given in figure 51.

Additionally, a few comments were given on full depth glide snow avalanches. Full depth glide snow avalanches are not in the focus of this study. Thus, these comments are not listed and discussed.

Most avalanches are artificially released during warm weather periods ($p \leq 0,01$) - especially large avalanches ($p \leq 0,05$) are more frequently triggered by avalanche control services who conduct many control operations during warm periods.

No matter if they release small, medium or large wet snow avalanches - those avalanche control services who often release wet snow avalanches do have steeper release zones ($p \leq 0,05$). Especially loose wet snow avalanches are more frequently observed in steep terrain ($p \leq 0,05$) - secondary releases are also more frequently observed ($p \leq 0,05$) in steep terrain. In areas with many rocky slopes more small avalanche activity is observed ($p \leq 0,05$).

Secondary slabs are most frequently triggered by medium and large wet snow avalanches ($p \leq 0,05$). Secondary slabs are more frequently observed in rocky terrain ($p \leq 0,01$) - maybe triggered by a primary loose wet snow avalanche.

The frequency of wet loose snow and wet slab avalanches is related to the frequency of small and medium-sized surface and ground snow avalanches ($p \leq 0,05$). Medium ($p \leq 0,01$), large ($p \leq 0,05$) and slab ($p \leq 0,05$) avalanches are more frequently observed on gramineous slopes. Avalanche control services with easterly release zones observe significantly more wet loose snow avalanches ($p \leq 0,05$). However, loose wet snow avalanches seem to be less frequent in release zones above 2500m.

4.3.5 Release success rate and reduction of closure times

The release success rate in wet snow conditions is generally lower than in dry snow conditions (figures 45 and 46): According to the survey, the average release success rate for dry snow avalanches is about 60% (N=48). The average release success rate for wet snow avalanches is only about 38% (N=47). However, about 24% of the respondents reach a success rate higher than 60% in wet snow conditions.

Avalanche control services with a success rate higher than 70% exclusively operate in inneralpine areas. Two of them mentioned that they had been practicing artificial release of wet snow avalanches for more than 20 years. They have improved their success rate through the gain of experience. Most of the respondents could not observe improving release success rates over the last years (90%).

The reasons for negative release success are often connected with the difficult timing (5) of control operations. Many respondents concede that, at least sometimes, control operations were started too early (62%) or too late (54%) on the particular day. Details are shown in figure 53.

About 62% of the respondents are able to reduce closure times through artificial release of wet snow avalanches. However, 34% of the respondents cannot significantly reduce closure times in wet snow conditions - maybe because of additional problems with full depth glide snow avalanches (2) or lack of release success. Additionally, three respondents noted that they prefer closure because of the damage potential of wet snow avalanches. Compared to dry snow conditions, wet snow avalanches might cause increased pollution through dirt debris because even small or medium-sized wet snow avalanches frequently develop to full depth avalanches.

Those avalanche control services who can reduce closure times do have higher release success rates in wet ($p \leq 0{,}001$) and dry ($p \leq 0{,}05$) snow conditions. They trigger more wet loose and ground slab avalanches ($p \leq 0{,}01$) and their relative amount of explosives used for the release of wet snow avalanches is significantly higher ($p \leq 0{,}05$). Within the forecasting process they rate class I instability factors and class III snowpack factors ($p \leq 0{,}05$) as more important. Helicopter delivery is more frequently used to release wet snow avalanches ($p \leq 0{,}05$). Test releases are also more frequently applied ($p \leq 0{,}05$).

Avalanche control services with a release success rate of more than 60% in wet snow conditions trigger significantly more slab and ground avalanches ($p \leq 0{,}05$). They also have higher success rates in dry snow conditions ($p \leq 0{,}05$). They rate NXD programs and information on snowpack structure as more important ($p \leq 0{,}05$), and they use bigger charge sizes (p≤0,05). They expect to achieve best results by placing charges on or above the snowpack to release wet loose snow avalanches (p≤0,05). There is no obvious relation between the amount of explosives and the release success rate.

Figure 45: Release success rate in wet snow conditions

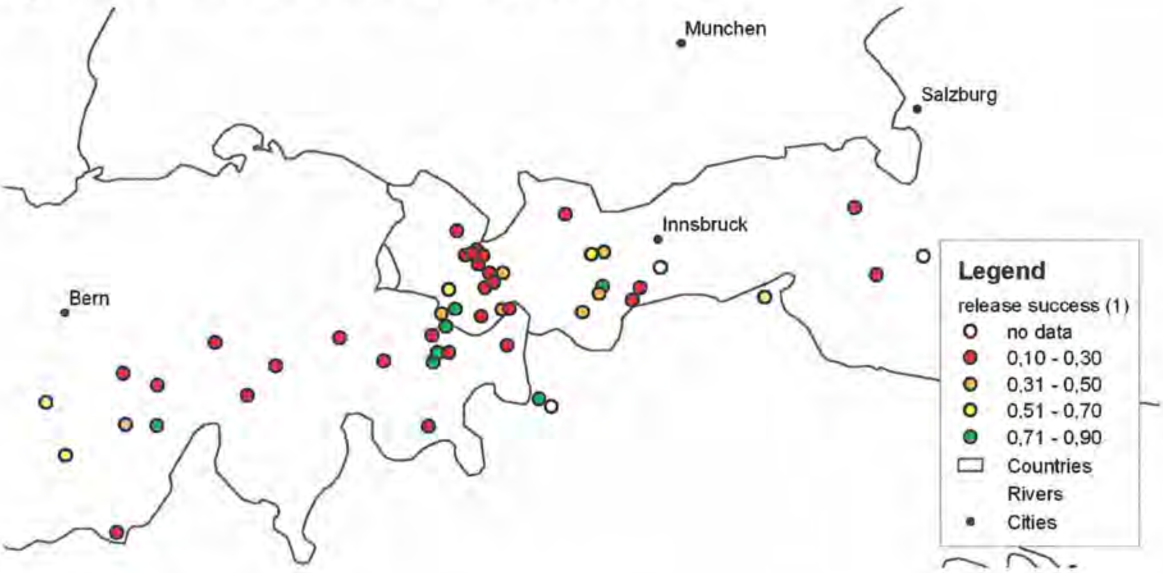


Figure 46: Release success rate in dry snow conditions

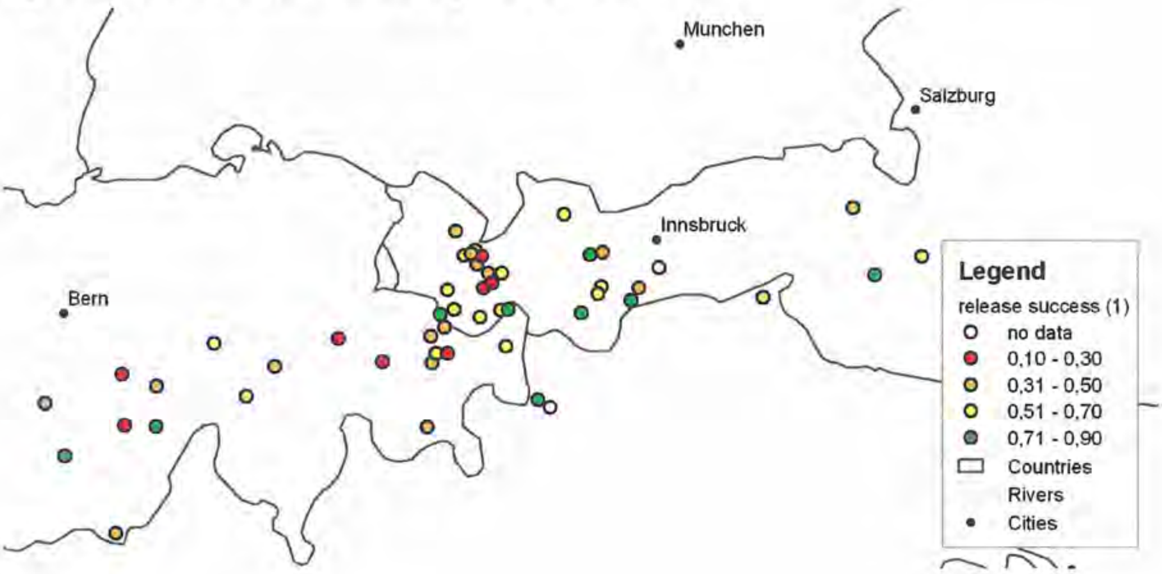


Figure 47: Triggered types of wet snow avalanches (N=50)

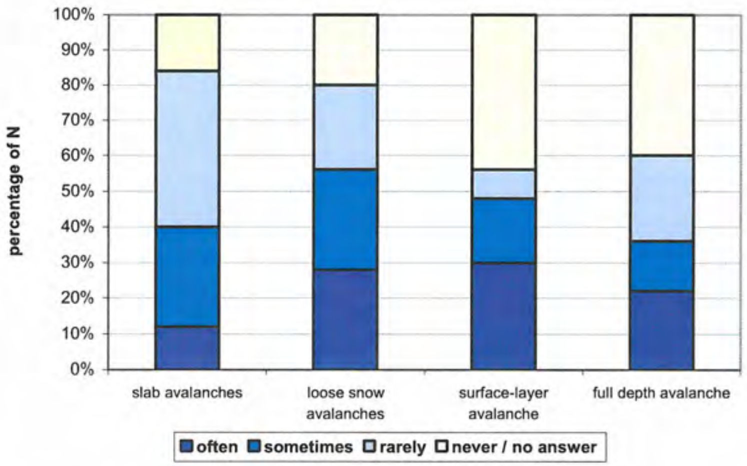


Figure 48: Index sum of triggered wet snow avalanche types

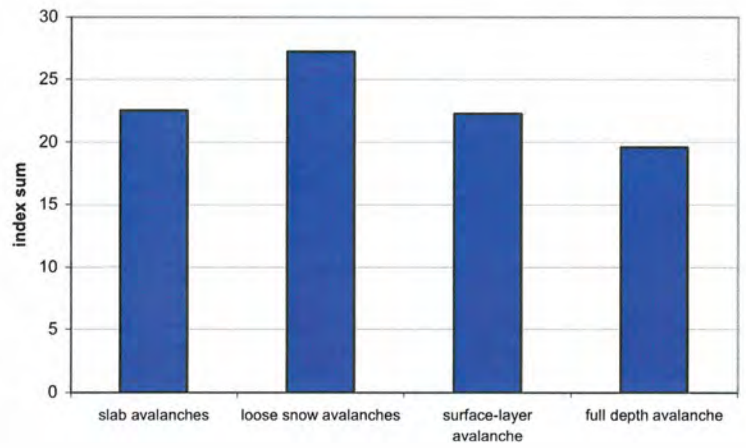


Figure 49: Size of triggered wet snow avalanches (N=50)

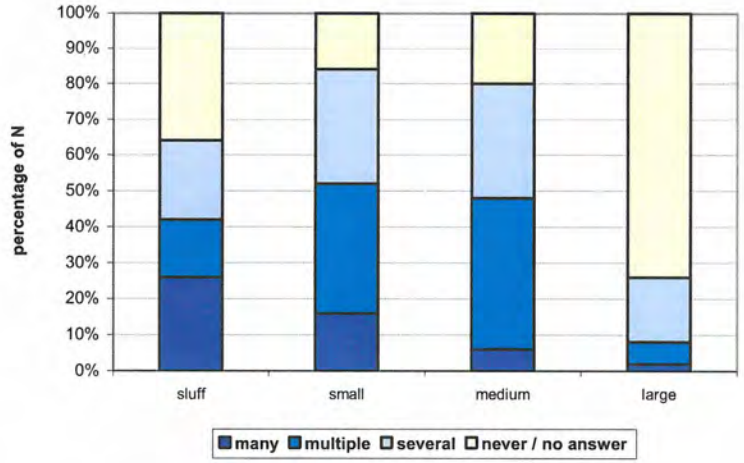


Figure 50: Index sum of triggered wet snow avalanche sizes

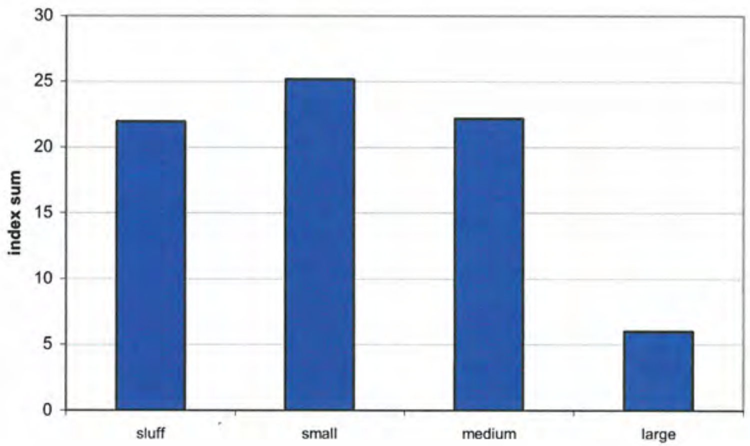


Figure 51: Secondary and remote triggered wet snow avalanches (N=50)

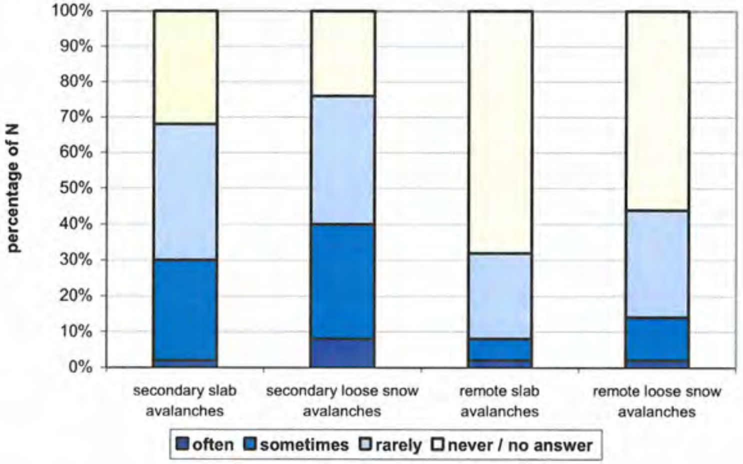


Figure 52: Release success rates for wet & dry snow avalanches

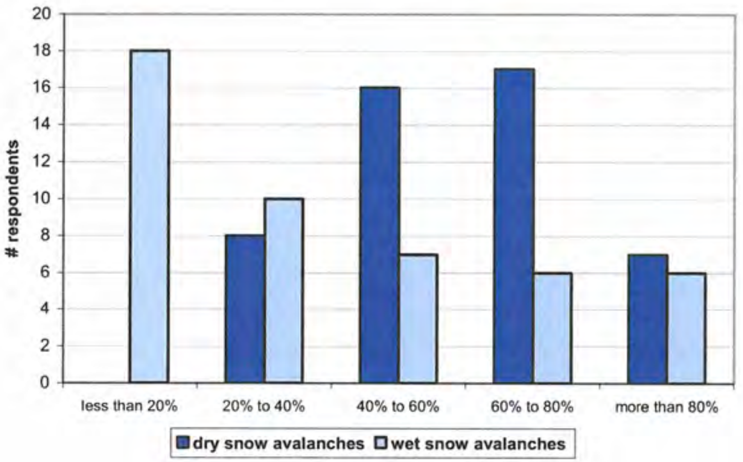
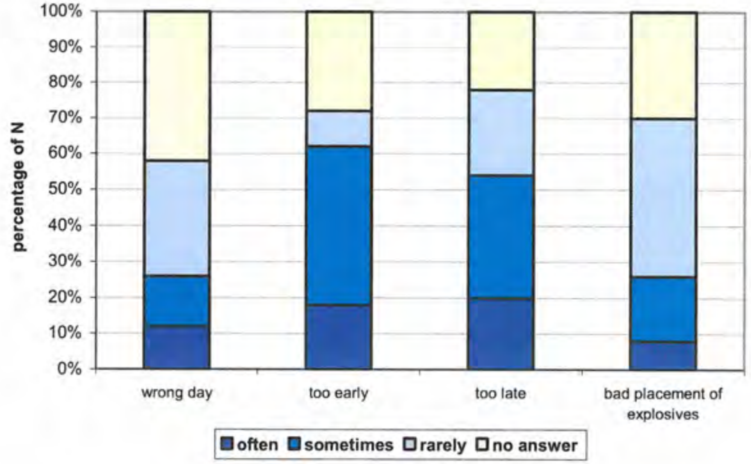


Figure 53: Reasons for negative release success (N=50)



4.3.6 Differences between countries

Release zones of the participating Austrian avalanche control services are generally lower located ($p \leq 0,05$). Because of the lower elevation, the number of control operations is significantly higher ($p \leq 0,05$) especially in April ($p \leq 0,05$). However, in late spring time they conduct fewer control operations. Wet snow avalanches during and after wet snowfall are more common in Austria ($p \leq 0,05$). Steep release zones for wet snow avalanches of more than 40° of incline are also more common in Austria ($p \leq 0,001$). Swiss avalanche control services generally have less inclined release zones ($p \leq 0,05$). Ground wet snow avalanches and surface wet snow avalanches are less frequently triggered in Austria ($p \leq 0,05$).

Autonomous devices are more frequently used in Austria to control avalanches ($p \leq 0,05$), whereas projectile devices are mostly used in Switzerland to control dry and wet snow avalanches ($p \leq 0,001$). The participating Swiss avalanche control services are responsible for more ski slope kilometers ($p \leq 0,001$) and in total they use more explosives to control avalanches ($p \leq 0,05$). Because they are generally higher located, the portion of explosives used for wet snow avalanches is lower ($p \leq 0,05$). To control dry snow avalanches, they use more explosives per release point ($p \leq 0,05$) - this may be related to their higher elevation. Swiss control services often use the same charge sizes for dry and wet snow avalanches ($p \leq 0,05$). Wrong charge placement is more frequently seen as a reason of negative release success in Switzerland ($p \leq 0,05$). Test releases are more frequently rated as very important in Austria ($p \leq 0,05$).

No significant differences in release success rates and in reduction of closure times could be observed between the participant Austrian and Swiss avalanche control services. The Italian avalanche control services are not discussed in detail. Because of the small sample size (N=3), the interpretation could easily lead to wrong conclusions.

4.3.7 Differences between avalanche control operations for ski areas and highways or roads

For those avalanche control services who exclusively work for ski areas, information on snowpack parameters are better available ($p \leq 0,05$) because they do have better access to release zones or comparable terrain. They rate information on the snowpack basement ($p \leq 0,01$), snowpack height decrease ($p \leq 0,05$), snowpack surface temperature ($p \leq 0,05$), relative humidity ($p \leq 0,05$) and cloudiness during the night ($p \leq 0,05$) as more important than those avalanche control services who also work for road and highway safety. Rain on snow events are less frequently a trigger for wet snow instabilities in ski areas ($p \leq 0,05$).

Avalanche control services in ski areas usually work more with ropeway delivery and hand thrown charges in wet and dry snow conditions ($\leq 0,05$). The relative amount of explosives used for wet snow control operations is lower for avalanche control services who exclusively work for ski areas.

4.3.8 Matter of size

Avalanche control services with more than 100 release points in dry snow conditions do rate numerical avalanche forecasting tools (NXD) in dry and in wet snow conditions as more helpful ($p \leq 0,05$). Probably many of the avalanche control services with less than 100 release points do not have such a forecasting tool available. Snowpack information is also rated more important by those avalanche control services with more than 100 release points ($p \leq 0,05$). Their operating area is generally larger - expressed by slope kilometers ($p \leq 0,01$). They generally work in more challenging terrain because the number of release points per slope kilometer is significantly higher ($p \leq 0,05$). They also have more release points prone to wet snow avalanches ($p \leq 0,05$). Thus, the number of control operations in wet snow conditions is significantly higher ($p \leq 0,05$). However, the relative portion of release points prone to wet snow instabilities is lower ($p \leq 0,05$). Avalanche control services with more than 100 release points generally use bigger charge sizes for wet snow avalanche release than their colleagues with fewer release points ($p \leq 0,05$). Most of them also expect that the best timing to release wet slabs during warm and sunny periods is just after the last sundown ($p \leq 0,05$). Wrong day is more often rated as a reason for negative success by those with more than 100 release points ($p \leq 0,01$). Naturally, the total amount of explosives is related to the number of release points: Those with more than 100 release points do use significantly more explosives ($p \leq 0,001$) in total but also in wet snow conditions ($p \leq 0,01$). The bigger the operating area, the more control operations are conducted. Thus, most of the release methods are generally more frequently used by control services with more than 100 release points.

An other analysis compares avalanche control services with more and less than 30 release points for wet snow avalanches. Those with less than 30 release points do have significantly less southerly exposed release zones ($p \leq 0,05$). Snowpack information is rated as less important ($p \leq 0,05$) by those who have more than 30 release points for wet snow avalanches. Helicopter and hand delivery is more frequently used for triggering wet snow avalanches by those who have more than 30 release points ($p \leq 0,05$). Naturally, they use more explosives ($p \leq 0,05$) and trigger more wet snow avalanches ($p \leq 0,05$).

No significant relationship could be observed between release success rate and the number of release points - neither in wet nor in dry snow conditions.

4.4 Discussion

The objective of the survey is to collect experience and knowledge of practitioners and to provide statistical data. About 112 avalanche control services in Austria, Switzerland and South Tyrol (Italy) were approched with a questionnaire. In Tyrol an online survey was conducted. Overall, 78 avalanche control services responded: Thereof 50 with a completed questionnaire. The other 28 responded that they did not have any experiences with wet snow avalanches. The number of questionnaires returned indicates the general interest in the research topic. Results of the analysis are discussed in the following part according to the research questions of the survey.

Where and under which weather situations are wet snow avalanches frequently artificially released? What is the best timing for control operations?

Release zones are mostly situated in southerly slopes from 2000 m to 2500 m. No control operations are conducted below 1500 m. Potential release zones below 1500 m might be forested (PERZL, 2005) or the generelly thin snow cover might not enable relevant wet snow avalanche activity.

Wet snow avalanches are mostly triggered during precipitation-free periods with high radiation and high temperatures. Avalanche control services agree that control operations in warm spring conditions are most effective after several hours of solar radiation. However, many avalanche control services expect the best moment for control operations just after the last sundown. The effect of a refreezing crust on the snowpack surface that is leading to a better fracture propagation is also mentioned in literature (STOFFEL, 2013). However, some respondents mentioned that the best moment is just before sunset. Respondents obviously disagree about the best timing for control operations. Further investigations are necessary.

Rain on snow events are a common trigger for wet snow instabilities: Many respondents state that, at least sometimes, rain on snow events are leading to control operations. Timing of control operations during rain on snow events might depend on the prevailing snowpack conditions.

According to the survey, wet snowfall and rapid warming after snowfall are less frequent triggers for control operations. The reasons might be the lower frequency of such weather situations or resulting small-sized avalanches (surface layer avalanches) that do not endanger infrastructure.

Forecasting wet snow avalanche activity is difficult. Respondents mentioned that several weather and snowpack parameters have to be considered within the forecasting and evaluation process. Parameters and values may differ according to the prevailing weather situation. The survey agrees with another survey by TECHEL (2010) where 'forecasters and researchers alike agree that direct stability information (class I data), and in particular natural avalanche observations, are by far the best indicator of wet snow instability.' Information sources on snowpack (class II) and metereological (class III) data are also highly ranked in the survey - especially snowpack observations and weather stations. Study plots and NXD programs are less frequently used to forecast wet snow instabilities. Study plots are placed in flat areas, thus, the snowpack may differ from the snowpack in the start zones. The NXD program is usually fitted for dry snow avalanches and such programs are not available for many avalanche control services.

Which release methods are used for wet snow avalanches? Are different release methods especially suitable for wet snow avalanches?

Charge placement in wet snow conditions is mostly done from helicopter or by hand. Compared to dry snow conditions, especially hand and helicopter delivery of explosives and mechanical triggers like ski cutting and groomers are more frequently used to release wet snow avalanches. Hand charging and ski cutting were most frequently cited as an especially suitable method in wet snow conditions.

Even if most of the respondents expect to have the best impact with charges on or above the snowpack, they use methods where charges are generally placed in the snowpack. Other factors, like flexible charge placement within the release zone, seem to be more important.

Autonomous devices are less frequently used in wet snow conditions. The reasons may be empty release zones around the devices because of frequently triggered dry snow avalanches. Projectile devices are less frequently used in wet snow conditions. As in these situations there are hardly any weather limitations, it is possible to use helicopter charging instead of projectile devices. All in all, helicopter charging is cheaper, less laborious and generally more effective because bigger charges can be used.

However, many respondents estimate that it is not possible to determine the most effective release method for wet snow conditions. The result of the survey is still not consistent in charge positioning. Positioning and placement have not been investigated for different fracture types.

How effective is the artificial release of wet snow avalanches and is it possible to significantly reduce closure times?

Artificial release of wet snow avalanches is feasible. The release success rate in wet snow conditions is generally lower than in dry snow conditions. The reasons for negative release success are often connected with the difficult timing of control operations.

Negative release results are proof of a stable snowpack at a specific moment. For decision making, negative release results in dry and wet snow conditions should be distinguished: Whereas the stability of dry snowpacks usually improves with time after precipitation events (of course this is not valid for persistent weak layers), the stability of wet snowpacks generally decreases with time of radiation and warming. Therefore, negative release results only grant stability for a limited time frame. The concept of test blasting in wet snow conditions is more focused on determining instability contrary to dry snow avalanches (determining stability).

Decision making on positive release results and empty starting zones is, therefore, much easier. About two thirds of the avalanche control services can reduce closure times significantly. The majority of them has a release success rate of 40% or more.

There are also some avalanche control services who prefer closure because of the unpredictable damage potential of wet snow avalanches.

What is the relevance of artificial release of wet snow avalanches compared to dry snow avalanches?

According to the survey, on average about one third of the dry snow avalanche release points is prone to wet snow avalanches. About 13% of the total amount of explosives are used to control wet snow avalanches. In dry snow conditions artificial avalanche release deals mainly with slab avalanches. In wet snow conditions loose snow avalanches are more important than slabs.

The following list points out the inconsistencies I realized in the questionnaire and the limitations of the survey:

- The snowpack moisture has not been included in the list of important snowpack parameters to determine wet snow instability. Some respondents additionally mentioned snowpack moisture as an important parameter to assess wet snow instability.
- Snow stability tests and weather forecasts are other possible tools in the assessment process of wet snow instabilities. These tools have not been included in the questionnaire. Only few respondents additionally mentioned those tools.
- There was no explicit delineation to full depth glide snow avalanches. Some of the respondents may have included those avalanche types into their response.
- Questions related to the frequency of events do have ranked answers like, for example, often - sometimes - rarely. The time frame of the answer frequency has not been defined. Therefore, it is open to the respondent to interpret the time frame, whether it is one winter season or several winter seasons.
- Return rates are high within some regions (Vorarlberg, Grisons, Western Tyrol) and significantly lower in other regions (Salzburg, Eastern Tyrol). The reasons may be: limited experience and fewer problems with wet snow avalanches. The expected reasons for high return rates are personal contacts to participating avalanche control services.

- The survey was focusing on the German-speaking regions within Switzerland and South Tyrol (Italy). No Italian questionnaire was developed. Only limited French questionnaires were posted.
- The sample of avalanche control services might not be representative for extrapolation of numerical data. Overall, the dataset consists of only 50 questionnaires. Because of the limited sample size, the results of statistical tests have only limited value and should be analysed with caution.

4.5 Conclusion

The intention of the survey was to assess the current state of artificial release of wet snow avalanches. According to the survey, control operations are frequently carried out in many ski areas and above highways or roads with varying release success. However, artificial release of wet snow avalanche is feasible and helps to reduce closure times significantly in many areas. Further research is needed to specify the timing for control operations and the effectiveness of release methods with regard to different types of wet snow avalanches. The survey leads to the following research questions:

Specify the timing of control operations for different snowpack and weather situations.

Specify weather and snowpack characteristics to forecast wet snow avalanche activity.

Investigate the most effective release methods and the best charge placement for different types of wet snow avalanches.

5 Expert Interviews

5.1 Introduction

Chapters 2 and 3 introduced the theoretical concepts for wet snow avalanches and artificial avalanche release. Different weather situations lead to water input into the snowpack either by inducing melting processes in the top snowpack layers, by rain or by a combination of melting and rain. Depending on the amount of provided liquid water, the current snowpack structure and the terrain conditions, different release mechanisms cause wet slab or wet loose snow avalanches. Artificial avalanche release in wet snow conditions seems to be difficult because of the lower fracture propagation and because explosion shock waves, stress waves and N-waves attenuate strongly with increasing liquid water content of the snowpack. Nevertheless, according to the survey presented (see chapter 4), artificial release of wet snow avalanches is feasible and control operations are frequently done in many ski areas and above highways or roads. However, further research is needed to specify the timing for control operations and the effectiveness of release methods with regard to different types of wet snow avalanches.

The objective of the expert interviews is, therefore, to collect the experience and knowledge of experts. Therefore, chosen experts in Austria, Switzerland and South Tyrol (Italy) are interviewed. The general research questions are presented in the following list.

Research questions:

Specify the timing of control operations for different snowpack and weather situations.

Investigate the most effective release methods and the best charge placement for different types of wet snow avalanches.

5.2 Methods

5.2.1 Expert selection and interviews

Of the participants of the survey 14 respondents were chosen for guideline-based expert interviews (MIEG and NÄF, 2005). The criteria for choosing were mainly the yearly amount of explosives used for wet snow avalanches and personal recommendations of members of the SLF and the Tyrolean avalanche control service. The chosen experts have at least 10 years of experience (MIEG and NÄF, 2005). Table 5 compares keyfacts of the chosen experts with those of the survey participants. On average, the chosen experts use more explosives to control wet snow avalanches. Relative to the survey more Swiss experts and more experts working on roads and highways have been interviewed (table 5). On average, the experts interviewed do have more release points compared to the survey participants. The release success rate of the chosen experts is sligthly higher than the release success rate of the survey participants.

Table 5: Keyfacts of interview partners and survey respondents

	Interviews (N=14)			Survey (N=50)		
	min.	max.	Ø / #	min.	max.	Ø / #
Country						
Austria [#]			6 (43%)			27 (54%)
Switzerland [#]			7 (50%)			20 (40%)
South Tyrol (Italy) [#]			1 (7%)			3 (6%)
Operating area						
ski area [#]			12 (86%)			47 (94%)
ski area size [slope km]	10	140	66	10	280	71
roads / highways [#]			7 (50%)			14 (28%)
community [#]			4 (29%)			10 (20%)
release points dry snow avalanches [#]	18	400	130	2	475	87
release points wet snow avalanches [#]	6	150	46	5	379	30
southerly exposed release areas [y=1/n=0]			12 (86%)			39 (78%)
northerly exposed release areas [y=1/n=0]			7 (50%)			30 (60%)
medium sealevel [m]	2000	2750	2384	1750	2750	2235
Control operations						
total amount explosives [kg]	150	10440	3040	90	10500	2344
amount explosives for wet snow avalanches [kg]	50	1280	441	5	1320	261
control operations in wet snow conditions [#]	8	26	14	2	27	12
release success rate dry snow avalanches [%]	30	90	65	30	90	60
release success rate wet snow avalanches [%]	10	90	43	19	90	38

5.2.2 Guideline-based interviews

An open guideline was developed for the interviews in German and French language. The guideline was structered into 5 categories:

(1) Introduction and general questions.

(2) Definition and classification of wet snow avalanches.

(3) Timing of control operations in different weather and snowpack conditions.

(4) Release methods, charge placement and charge size selection.

(5) Release success.

The complete guideline is attached in appendix B (German version). Each expert was visited at his hometown or working place between May and October 2008. Interviews were conducted according to the guideline presented and digitally recorded with a dictophone. The length of the interviews was between 60 minutes and 120 minutes. In total, 14 interviews were conducted. The interviews recorded were transcribed with the software 'f4 audio'. The final database consists of 14 text datasets with a total of 95.000 words.

5.2.3 Data analysis

Based on literature research and survey results, hypotheses were developed (MIEG and NÄF, 2005). The database was analysed according to the basic principles of the qualitative content analysis (MAYRING, 2001). Deductive category application with pre-formulated, theory-derived aspects was applied (MAYRING, 2001). Different categories were defined for the analysis of each hypothesis. Categories were coded with yes/no (nominal), numerical or textual information.

Nominal categories were analysed by counting answer possibilities. Categories with numerical answer possibilites were analysed with box plots. Because of the limited sample size, only descriptive statistics were applied. Textual information was structured and summarized. Final results were analysed qualitatively for hypothesis testing. A list of all hypotheses and categories is given in chapter 5.2.4. The coding process and data analysis was done using the 'MAXQDA' software.

5.2.4 Hypothesis formulation and category definition

According to the research questions, hypotheses were formulated. Different coding categories for the interview transcripts are presented for testing the hypotheses.

5.2.5 Timing of control operations

Hypothesis A: The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure.

Investigations by CONWAY (1988), TECHEL (2008, 2010) and MITTERER (2012) revealed that, if snowpack stability is close to critical before first (or repeated) wetting occurs, not much liquid water is required for weak snowpack layers to become unstable. If the snowpack is stable, a high amount of liquid water has to be concentrated in order to develop wet snow instabilities. CONWAY (1988) summarizes that the loss of strength with the introduction of water into a layer depends on the structure and type of snow: 'The final crystal type tends toward large rounded grains. The greater the change in crystal shape necessary to achieve this final state, the more quickly the snow becomes unstable with the introduction of water.'

Table 6: Coding categories for hypothesis A

A.1.	Weak snowpacks (persistent grains) ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	nominal
A.2.	New snow ... a. ... does not need much liquid water to become unstable. b. ... needs much liquid water to become unstable.	nominal
A.3.	Stable snowpacks ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	nominal
A.4.	Homogeneous ripe snowpacks ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	nominal

Hypothesis B: Prediction of wet snow instabilities with regard to the necessary amount of liquid water is difficult during warm weather periods. Instabilities through rain on snow events are more predictable.

According to the investigations presented in chapter 2.4, wet snow avalanches are difficult to forecast (MITTERER et al., 2009; TECHEL and PIELMEIER, 2009). According to the survey, warming and radiation during spring melt season are the most common triggers for wet snow avalanches. However, the onset of avalanche activity is difficult to predict (TECHEL and PIELMEIER, 2009).

Table 7: Coding categories for hypothesis B (I)

B.1.	Control operations during warm periods with high radiation are foreseeable ... a. ... more than 24 hours in advance. b. ... on the morning of the specific day at the earliest. c. ... a few hours before the control operation starts.	nominal
B.2.	Snowpack factors during warm weather periods that increase the chance of wet snow avalanche release.	textual
B.3.	Weather factors during warm weather periods that increase the chance of wet snow avalanche release.	textual

Rain on snow events are a frequent trigger for wet snow avalanche cycles in maritime snow climates (HEYWOOD, 1988). According to the survey, they are also a common trigger in the Alps - especially in lower elevations. BAGGI and SCHWEIZER (2009) observed the amount of precipitation as a significant parameter related to wet snow instability. Treshold amounts and intensities for precipitation events triggering wet snow avalanches depend on snowpack structure (CONWAY and RAYMOND, 1993; CONWAY et al. 2008). The precipitation amount and intensity is well forecasted by metereological models.

Table 8: Coding categories for hypothesis B (II)

B.4.	Wet snow instabilities caused by rain are observed ... a. ... more than once in a winter season. b. ... once or less in a winter season.	nominal
B.5.	Control operations triggered by rain on snow events are foreseeable ... a. ... more than 24 hours in advance. b. ... when rain has started at the earliest.	nominal
B.6.	Snowpack factors during precipitation periods that increase the chance of wet snow avalanche release.	textual
B.7.	Weather factors during precipitation periods that increase the chance of wet snow avalanche release.	textual

Hypothesis C: During warm weather periods with high radiation, the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation.

Chapter 2.2.4 describes physical and mechanical properties of wet snow. Multiple investigations reveal that strength of snow decreases exponentially (YAMANOI and ENDO, 2002; IZUMI and AKITAYA, 1985) or abruptly at the transition from the pendular to the funicular regime (KATTELMANN, 1984; COLBECK, 1982; AMBACH and HOWORKA, 1965; KATTELMANN, 1987; BRUN and REY, 1987; BHUTIYANI, 1994). Persistent weak layers already change strength abruptly at a lower liquid water content (TECHEL, 2008, 2010; CONWAY et al., 1988; MITTERER, 2012).

Table 9: Coding category for hypothesis C

C.1.	The chance of successful release for wet snow avalanches increases ... a. ... exponentially or abruptly with time and intensity of radiation and warming. b. ... lineary or steadily with time and intensity of radiation and warming.	nominal

Hypothesis D: In fully-wet snowpack conditions timing of control operations just after the last sundown increases fracture propagation potential - however, the window of success is very short.

Chapter 2.3.1 describes the observation of MCCLUNG and SCHAERER (2006): They report scattered thin wet slab avalanches releasing 'after slopes become covered by shadows as the sun sets. One explanation is that surface cooling causes the release of a slab that is already in tension due to water lubrication of an interface below the surface. Snow with low water content (as would be expected near the surface) is known to contract as it freezes, this effect can rapidly increase tensile stresses.'

Table 10: Coding categories for hypothesis D

D.1.	When control operations in fully-wet snowpack conditions were conducted just after the last sundown, ... a. ... the release success for wet snow avalanches increases. b. ... fracture propagation potential for wet snow avalanches increases. c. ... the release success for wet snow avalanches decreases.	nominal
D.2.	The release success in transitional snowpacks ... a. ... decreases suddenly when the slope gets covered by shadow. b. ... increases when the slope gets covered by shadow.	nominal

5.2.6 Effectiveness of release methods

Hypothesis E: Different types of wet snow avalanches exist. Wet loose snow avalanches are most frequently released. Slab avalanches are less frequently triggered and they do have different morphologies. The expected avalanche type depends on snowpack properties.

According to the survey, wet loose snow avalanches are more frequently triggered than wet slab avalanches - especially in very steep terrain. Different formation mechanisms for wet snow avalanches were discussed in chapter 2.3. Wet loose snow avalanches form through uniform wetting of the upper snowpack layers or the whole (shallow) snowpack (homogeneous layering). According to chapter 2.3.1 obviously wet snow avalanches can release in fully-wetted snowpacks that have already undergone wet snow metamorphism and transitional snowpacks during the first serious wetting. Differences in snowpack structure and wetting are discussed in detail in chapter 2.3.1.

Table 11: Coding categories for hypothesis E

E.1.	Expert triggers wet loose snow avalanches ... a. ... more frequently than wet slab avalanches. b. ... less frequently than wet slab avalanches.	nominal
E.2.	Expert triggers ... a. ... wet loose snow avalanches. b. ... no wet loose snow avalanches.	nominal
E.3.	Expert triggers ... a. ... wet slab avalanches. b. ... no wet slab avalanches.	nominal
E.4.	Snowpack and terrain characteristics for wet loose snow avalanches.	textual
E.5.	Fracture line characteristics and fracture propagation of wet slab avalanches.	textual
E.6.	Snowpack and terrain characteristics for wet slab avalanches.	textual

Comments on full depth glide snow avalanches were not analysed because this avalanche type is not in the focus of this study.

Hypothesis F: The effective range in wet snow conditions is limited to the area around the crater zone. For charges fired on or above the snowpack, the effective range is slightly higher but still considerably lower than in dry snow conditions.

The impact of explosives on the snow cover is described in detail in chapter 3.1. The primary shock wave has a pushing effect on the snow cover (CHERNOUSS et al. 2006). The pushing effect is independent of the liquid water content of the snow cover. The maximum range of the primary shock wave depends on charge size and charge placement. Propagating N-shaped pressure waves attenuate very fast in fully-wet (GUBLER, 1977) and soft snowpacks. Compared to dry snow conditions, more energy is needed for fracture initiation and propagation in wet snowpacks. Thus, N-shaped pressure waves do have only a very limited impact in wet snow conditions.

Table 12: Coding categories for hypothesis F

F.1.	Effective range (wet snow) for airblasts.	numerical
F.2.	Effective range (wet snow) for charges fired within the snowpack.	numerical

Hypothesis G: To release wet loose snow avalanches, charge placement within the starting zone is crucial for release success. Charge size and charge position relative to the snow surface are secondary.

Wet loose snow avalanches are triggered by the pushing effect of the explosive shock wave or the pushing effect of a mechanical trigger. Because of the point release mechanism, the effective range of a blast is not important as long as the right release point is chosen.

Table 13: Coding categories for hypothesis G

G.1.	Charge placement for the release of wet loose snow avalanches.	textual
G.2.	To release wet loose snow avalanches, ... a. ... charge position is secondary for release success. b. ... charge position on or above the snowpack improves release success significantly. c. ... charge position in the snowpack improves release success significantly.	nominal
G.3.	To release wet loose snow avalanches, ... a. ... charge size is secondary for release success. b. ... bigger charge size improves release success significantly.	nominal
G.4.	Specifics of release methods with regard to the release of wet loose snow avalanches.	textual
G.5.	Snow entrainment and secondary releases through triggered avalanches.	textual

Hypothesis H: Charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches.

Like in dry snow conditions, wet slab avalanches are triggered by explosives through additional stress on the slab and the underlying weak layer. Release mechanisms of wet slab avalanches (see chapter 2.3) are poorly understood. However, the fracture propagation potential of wet snow is generally lower than in dry snow conditions (see chapter 2.2). Conclusively, more energy is needed for fracture initiation and propagation.

Table 14: Coding categories for hypothesis H

H.1.	Charge placement for the release of wet slab avalanches.	textual
H.2.	To release wet slab avalanches, ... a. ... charge position is secondary for release success. b. ... charge position on or above the snowpack improves release success significantly.	nominal
H.3.	To release wet slab avalanches, ... a. ... charge size is secondary for release success. b. ... bigger charge size improves release success significantly.	nominal
H.4.	Snow entrainment, secondary releases and remote triggering through wet snow avalanches.	textual

5.3 Results

5.3.1 Timing of control operations

Hypothesis A: The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure.

Experts agree that weak snowpacks (persistent grains) and new snow do not need much liquid water to become unstable. Stable snowpacks need much more liquid water to provoke wet snow instabilities. However, with regard to homogeneous, ripe snowpacks opinions differ among experts (table 15).

Table 15: Results for coding categories A.1. - A.4.

Coding categories:		a.	b.	n. a.
A.1.	Weak snowpacks (persistent grains) ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	7	-	7
A.2.	New snow ... a. ... does not need much liquid water to become unstable. b. ... needs much liquid water to become unstable.	7	-	7
A.3.	Stable snowpacks ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	-	10	4
A.4.	Homogeneous ripe snowpacks ... a. ... do not need much liquid water to become unstable. b. ... need much liquid water to become unstable.	4	4	6

In general, the hypothesis that the necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure can be verified. However, there is no consistent opinion with regard to the reaction of homogeneous ripe snowpacks to the input of additional liquid water.

Hypothesis B: Prediction of wet snow instabilities with regard to the necessary amount of liquid water is difficult during warm weather periods. Instabilities through rain on snow events are more predictable.

The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure (hypothesis A). The available amount of liquid water depends on weather parameters. Signs of instability can be observed when instabilities have developed.

During warm weather periods with high radiation, the snowpack has to be in a basic disposition in order to develop wet snow instabilities on a given day. Experts mention the following signs of basic disposition for wet snow instabilities:
- Two thirds or more of the snowpack are isothermal.
- Moist or wet snowpack (layers).
- Shining snow surface.
- No or thin crust in the morning, caused by poor radiant emittance.
- Weak persistent snowpack basement.
- Warming influence of the ground on the snowpack basement.

The wetness stage of the snowpack may be less important for wet snow instabilities caused by rain on snow events because the high amount of liquid water can rapidly alter the snowpack temperature and wetness stage. The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure.

During warm weather periods with high radiation, liquid water is produced through melting upper snowpack layers. According to the experts, the following weather parameters support melt water production: diffuse and foggy radiation weather conditions, intense radiation, high minimum and maximum temperatures, high relative humidity, overcast nights and rapid warming after new snow. However, there are different opinions with regard to the influence of the wind: Foehn may provoke wet snow instabilities through wetting of the upper snowpack layers or prohibit wet snow instabilities through taking away humidity from the snowpack; cold winds may or may not have a stabilizing effect on the snowpack. During rain on snow events additional liquid water is provided through direct water input by precipitation (wet snowfall, rain). In addition, rain increases the melting rate in the upper snowpack layers - especially in new snow layers (rising snow line during a precipitation event) - and provides additional weight on the snowpack.

When wet snow instabilities develop, they are usually observed by the experts through the following signs of instability: High penetration depth (boot, ski, pole), tumbling snowballs on the snowpack surface and natural avalanches.

Table 16: Results for coding categories B.1., B.4., B.5.

Coding categories:		a.	b.	c.	n.a.
B.1.	Control operations during warm periods with high radiation are foreseeable ... a. ... more than 24 hours in advance. b. ... on the morning of the specific day at the earliest. c. ... a few hours before the control operation starts.	0	3	8	3
B.4.	Wet snow instabilities caused by rain are observed ... a. ... more than once in a winter season. b. ... once or less in a winter season.	3	5	/	6
B.5.	Control operations triggered by rain on snow events are foreseeable ... a. ... more than 24 hours in advance. b. ... when rain has started at the earliest.	5	0	/	9

According to the experts' opinion, control operations during warm periods with high radiation are foreseeable on the morning of the specific day at the earliest. Most experts decide whether or not to start a control operation only a few hours before (table 16). Decisions are based on current weather conditions, signs of instability and test releases. Only some experts observe wet snow instabilities caused by rain more than once in a season. According to the experts, control operations caused by rain on snow events are usually foreseeable for more than 24 hours in advance, (table 16) based on the forecasted amount of precipitation and the forecasted snow line (development).

The hypothesis that wet snow instabilities through rain on snow events are more predictable than wet snow instabilities during warm periods with high radiation can be verified.

Hypothesis C: During warm weather periods with high radiation, the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation.

One expert frequently observes sudden loss of stability within a time period of 30 minutes. Most experts believe that the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation. One expert estimates a linear increase. However, a linear increase may be appropriate for the entity of several release zones of different heights and aspects.

Table 17: Results for coding category C.1.

Coding categories:		a.	b.	n. a.
C.1.	The chance of successful release for wet snow avalanches increases ... a. ... exponentially or abruptly with time and intensity of radiation and warming. b. ... lineary or steadily with time and intensity of radiation and warming.	6	1	7

In general, the hypothesis that during warm weather periods with high radiation the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation can be verified.

Hypothesis D: In fully-wet snowpack conditions timing of control operations just after the last sundown increases fracture propagation potential - however, the window of success is very short.

During warm weather periods with high radiation, the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation. Thus, the best timing for control operations is expected before radiation and temperature decrease significantly. However, some experts observed increased release success when control operations were conducted just after the last sundown in fully-wet snowpack conditions. Another group of experts observed that fracture propagation potential has increased just after the last sundown. One expert even reports scattered release success in the morning when a very wet snowpack was covered by a crust. However, there are also some experts who observed a sudden decrease of release success in fully-wet snowpack conditions just after the last sundown. In transitional snowpack conditions all experts agree that release success decreases suddenly when the slope gets covered by the shadow.

Table 18: Results for coding categories D.1., D.2.

Coding categories:		a.	b.	c.	n.a.
D.1.	When control operations in fully-wet snowpack conditions were conducted just after the last sundown, ... a. ... the release success for wet snow avalanches increases. b. ... fracture propagation potential for wet snow avalanches increases. c. ... the release success for wet snow avalanches decreases.	2	6	4	2
D.2.	The release success in transitional snowpacks ... a. ... decreases suddenly when the slope gets covered by shadow. b. ... increases when the slope gets covered by shadow.	6	0	/	8

The hypothesis that in fully-wet snowpack conditions timing of control operations just after the last sundown increases fracture propagation potential cannot be verified. Although many experts observed increased release success and fracture propagation potential, there are some experts who observed the opposite.

5.3.2 Effectiveness of release methods

Hypothesis E: Different types of wet snow avalanches exist. Wet loose snow avalanches are most frequently released. Slab avalanches are less frequently triggered and they do have different morphologies. The expected avalanche type depends on snowpack properties.

According to the interviews, most of the experts trigger wet loose snow and wet slab avalanches (table 19). Most of them trigger wet loose snow avalanches more frequently than wet slab avalanches (table 19). No expert mentioned that he triggers wet slabs more frequently.

The snowpack's structure does have an influence on the release type of a potential wet snow avalanche. According to the experts, wet loose snow avalanches release and develop to full depth avalanches when the whole snowpack consists of uniform homogeneous layers with wet snow grains formed by melt-freeze metamorphism. The whole snowpack is fully-wet (type 4 wetness classification, see figure 2), very soft and has only very low ram resistance comparable to type 1 of ram hardness classification (WIESINGER and SCHWEIZER, 2000). If only the upper snowpack layers consist of very soft and wet grains (type 2 wetness classification), surface wet loose snow avalanches develop. The upper layers may consist of wet snow grains formed by melt-freeze metamorphism or immediately wetted new snow. Harder and more stable snowpack layers beneath impede the development of full depth avalanches.

Table 19: Results for coding categories E.1. - E.3.

Coding categories:		a.	b.	n. a.
E.1.	Expert triggers wet loose snow avalanches ... a. ... more frequently than wet slab avalanches. b. ... less frequently than wet slab avalanches.	10	0	4
E.2.	Expert triggers ... a. ... wet loose snow avalanches. b. ... no wet loose snow avalanches.	13	0	1
E.3.	Expert triggers ... a. ... wet slab avalanches. b. ... no wet slab avalanches.	11	0	3

According to the experts, the fracture line of wet slab avalanches is usually irregular and scraggly. Sharp fracture lines are also possible but rare. Wet slab avalanches develop in snowpacks with weak basal layers and snowpacks with persistent weak layers or crusts. Additionally, slab like characteristics are necessary for fracture propagation. According to observations of the experts, slab characteristics can be obtained through remain crusts in (or upon) fully-wet snowpacks or through remaining harder midpack layers in fully-wet or transitional snowpacks. Usually, fracture propagation potential of wet slab avalanches is low. Thus, the fracture line has a width of only 10 m to 30 m. However, some experts report scattered avalanches with a fracture line width of 150 m to 300 m. Wet slab avalanches often develop in fully-wet snowpack conditions (type 4 wetness classification). Experts also report wet slab occurence in transitional snowpacks (type 2 wetness classification) and after new snow on wet snowpack layers (type 5 of wetness classification).

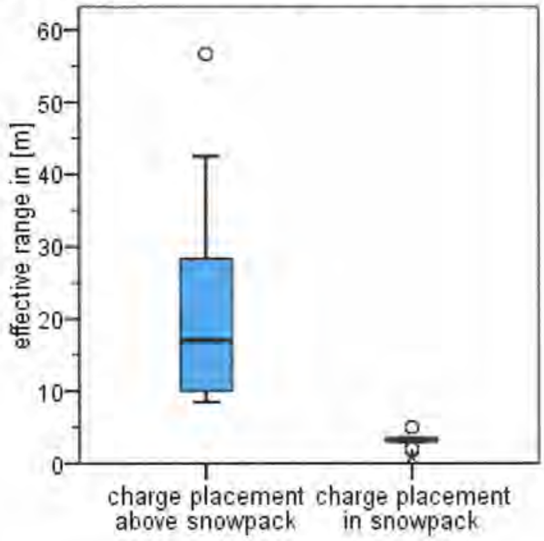
Among others, snowpack properties also depend on terrain characteristics. For example, weak basal layers are less frequently oberved in southerly aspects. Thus, there is an indirect influence of the terrain on the wet snow avalanche type. For example, very steep and structured rocky terrain in southerly aspects is prone to wet loose snow avalanches, whereas a more homogeneous slope in northerly aspects may be more prone to wet slab avalanches because of weak basal layers. Snowpack properties during spring time may also depend on the number and success of previous control operations.

Hypothesis E can be verified: Different types of wet snow avalanches exist. Wet loose snow avalanches are most frequently released. Slab avalanches are less frequently triggered and they do have different morphologies. The expected avalanche type depends on snowpack properties.

Hypothesis F: The effective range in wet snow conditions is limited to the area around the crater zone. For charges fired on or above the snowpack, the effective range is slightly higher but still considerably lower than in dry snow conditions.

Experts agree that the effective range for charges fired within the snowpack is limited to the area around the crater zone. Accoring to the experts the median radius for standard charges (1,5 to 2,5 kg) fired within the snowpack is 3,3 m. Details are given in figure 54. The experts' estimation for the effective ranges of standard charges placed above the snowpack differs considerably: The effective range is estimated between 8,5 m and 57 m with a median of 20 m radius. Details are given in figure 54. Compared to dry snow conditions, the effective range in wet snow conditions is expected to be reduced by a factor of between 10% and 66%.

Figure 54: Effective ranges in wet snow conditions (N=10)



Hypothesis F can be verified: The effective range in wet snow conditions is limited to the area around the crater zone. For charges fired on or above the snowpack, the effective range is slightly higher but still considerably lower than in dry snow conditions.

Hypothesis G: To release wet loose snow avalanches, charge placement within the starting zone is crucial for release success. Charge size and charge position relative to the snow surface are secondary.

Most of the experts agree that charge size is secondary for release success of wet loose snow avalanches. Only two experts expect to have a better release success with bigger charge sizes. The experts' opinions differ with regard to the relevance of charge positioning. Some experts think that charge position is secondary for release success. However, there are also experts who expect to improve release success by placing charges within or above the snowpack. Details are given in table 20.

Table 20: Results for coding categories G.2., G.3.

Coding categories:		a.	b.	c.	n. a.
G.2.	To release wet loose snow avalanches, ... a. ... charge position is secondary for release success. b. ... charge pos. on or above snowpack improves release success significantly. c. ... charge position in the snowpack improves release success significantly.	5	1	2	6
G.3.	To release wet loose snow avalanches, ... a. ... charge size is secondary for release success. b. ... bigger charge size improves release success significantly.	9	2	/	3

Generally, charge placement within the starting zone is seen crucial by many experts. In order to successfully release wet loose snow avalanches, experts recommend charge placement at areas where the snowpack is completely wet. Within the starting zone most-wetted areas are usually found at places with shallow snowpacks: For example, wind affected places near the ridge top. The steeper, the easier it is to release a wet loose snow avalanche. Steep parts of the starting zone usually also get more radiation. In rocky starting zones the snowpack is often very wet nearby and around rocks. The aspect of the chosen release point is also very important: Often different aspects are available within a starting zone especially in structured terrain. Thus, it is important to accurately choose the release point according to its aspect to hit the most-wetted place within the starting zone. Within big starting zones it is possible that conditions change according to sealevel. The uppermost part may be not wet enough, but lower parts may be ready for release.

Usually several charges are needed to empty a starting zone. In structured terrain one charge per couloir or gully is needed. In more homogeneous terrain the number of charges depends on the spreading of triggered loose snow avalanches. Charges are usually placed in the uppermost part of the starting zone near the ridge top or summit in order to maximize spreading and snow entrainment. Spreading and snow entrainment of wet loose snow avalanches mainly depend on terrain and snowpack conditions within the avalanche path. Secondary releases of wet loose and wet slab avalanches are frequently observed. Systematic triggering of wet loose snow avalanches in order to enforce secondary releases can help to empty a starting zone efficiently.

Experts use different release methods. Good release success is reported from helicopter charging, hand charging, projectile devices, avalanche towers and ropeways. Helicopter availability may be a problem with regard to the exact timing of control operations during wet snow conditions. Projectile devices may not have sufficient accuracy. Accessibility and safety concerns may limit the application of hand charging. Release point selection is limited with towers and ropeways. Ski cutting seems to be very efficient to release wet loose snow avalanches. Many experts use ski cutting predominantly to secure smaller slopes. One expert mentioned that he had no release success with Gazex devices: The snowpack around the Gazex devices is more dense because of frequent shots during the winter. Thus, the wetting stage does usually not correspond to the wetting stage in the rest of the starting zone.

There is no consistent opinion for charge size selection, best charge position and best release method among the experts. However, experts agree that charge placement is crucial for release success. Thus, hypothesis G can be verified: To release wet loose snow avalanches, flexible selection of release points is more important than optimizing the effective range when choosing the release method.

Hypothesis H: Charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches.

Experts agree that charge position on or above the snowpack and bigger charge sizes improve release success for wet slab avalanches significantly. Only one expert expects that charge size is secondary for release success. Details are given in table 21. According to the experts, charge placement is similar to dry snow conditions. However, more charges are needed because of the reduced effective range in wet snow conditions. Different types of secondary releases are observed: Surface slabs often trigger deeper layers. Sometimes adjacent wet slabs are triggered by a primary wet slab avalanche.

Table 21: Results for coding categories H.2., H.3.

Coding categories:		a.	b.	n. a.
H.2.	To release wet slab avalanches, ... a. ... charge position is secondary for release success. b. ... charge position on or above snowpack improves release success significantly.	0	6	8
H.3.	To release wet slab avalanches, ... a. ... charge size is secondary for release success. b. ... bigger charge size improves release success significantly.	1	4	9

The hypothesis that charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches can be verified.

5.4 Discussion

The objective of the expert interviews is to find out more about the timing of control operations and the most effective release method. Out of the survey participants 14 experts were chosen for interviews. Based on literature research and survey results, hypotheses were developed. Hypotheses were investigated by analysing interview results quantitatively and qualitatively. The results are discussed in the following part.

5.4.1 Timing of control operations

Experts agree with TECHEL (2008, 2010) and MTTERER (2012) that if snowpack stability is close to critical before first (or repeated) wetting occurs, not much liquid water is required for weak snowpack layers to become unstable. If snowpack stability is stable, a high amount of liquid water has to be concentrated in order to develop wet snow instabilities. Thus, the necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure and wetness stage.

The available amount of liquid water depends on weather parameters. During warm periods with high radiation, liquid water is produced through melting upper snowpack layers. The snowpack has to be in a basic disposition in order to develop wet snow instabilities on a given day. The basic disposition is characterized by already isothermal, moist or wet snowpack (layers) and / or potential weak layers. During rain on snow events liquid water is provided through direct water input by precipitation and melting of the upper snowpack layers. Thus, the wetness stage of the snowpack may be less important for wet snow instabilities caused by rain on snow events because the high amount of liquid water can rapidly alter the snowpack temperature and wetness stage.

The release type of a wet snow avalanche depends on the snowpack structure. With regard to snowpack layering and expected avalanche type, experts generally agree with previous studies presented in chapter 2.3: Wet loose snow avalanches form through uniform wetting of the upper snowpack layers or the whole (shallow) snowpack (homogeneous layering). Wet slab avalanches develop in snowpacks with weak basal layers and snowpacks with persistent weak layers or crusts. Additionally, slab like characteristics are necessary for fracture propagation. Experts observed wet slab avalanches in fully-wetted snowpacks that have already undergone wet snow metamorphism and transitional snowpacks during the first serious wetting.

According to the survey, warming and radiation during spring melt season are the most common triggers for wet snow avalanches. Experts agree with MITTERER et al. (2009) and TECHEL and PIELMEIER (2009) that the prediction of wet snow instabilities with regard to the necessary amount of liquid water is difficult during warm weather periods. Control operations during warm periods with high radiation are foreseeable on the morning of the specific day at the earliest. Most experts decide whether or not to start a control operation only a few hours before. Decisions are based on current weather conditions, signs of instability and test releases. According to the experts, instabilities through rain on snow events are more predictable, but rain on snow events are observed less frequently.

Most experts believe that the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation. Previous studies also reveal that strength of snow decreases exponentially or abruptly at the transition from the pendular to the funicular regime or at a lower liquid water content, if persistent weak layers are present. Thus, the best timing for control operations during warm periods with high radiation is before radiation and temperature decrease significantly.

However, some experts report increased release success when control operations were conducted just after the last sundown in fully-wet snowpack conditions. Another group of experts specifies that fracture propagation potential increases just after the last sundown. One expert even reports scattered release success in the morning when a very wet snowpack was covered by a crust. But there are also some experts who observed a sudden decrease of release success in fully-wet snowpack conditions just after the last sundown. In transitional snowpack conditions all experts agree that release success decreases suddenly when the slope gets covered by the shadow. Conclusively, more research work is necessary to find out more about fracture initiation and propagation in fully-wet snowpack conditions just after the last sundown.

5.4.2 Effectiveness of release methods

Contrary to dry snow conditions, wet loose snow avalanches are more frequently triggered in wet snow conditions. Experts' observations agree with survey results: Wet slabs are also triggered in wet snow conditions but far less frequently than wet loose snow avalanches. The release mechanisms of slab and loose snow avalanches are obviously different. Thus, the effectiveness of different release methods and best charge placement differs according to the type of avalanche.

For wet loose snow avalanches charge placement within the starting zone is crucial. To release wet loose snow avalanches, flexible selection of release points is more important than optimizing the effective range when choosing the release method. Survey results agree: Compared to dry snow conditions, release methods with flexible charge placement are more frequently used in wet snow conditions.

Secondary releases of wet loose and wet slab avalanches are frequently observed by experts and survey respondents. Experts and survey respondents agree: Systematic triggering of wet loose snow avalanches in order to enforce secondary releases, spreading and entrainment can help to empty a starting zone efficiently.

Like in dry snow conditions, wet slab avalanches are triggered by explosives through additional stress on the slab and the underlying weak layer. However, fracture propagation potential of wet snow is generally lower than in dry snow conditions. Conclusively, more energy is needed for fracture initiation and propagation. Thus, charge placement on or above the snowpack and bigger charge sizes are preferable in order to improve the effective range and release success.

Experts agree with STOFFEL (2001): In wet snow conditions the effective range for charges fired within the snowpack is limited to the area around the crater zone. The resulting median radius for standard charges (1,5 to 2,5 kg) fired within the snowpack is 3,3 m. The experts' estimation for the effective ranges for charges placed above the snowpack differs considerably: The effective range is estimated between 8,5 m and 57 m with a median of 20 m radius. Some experts mentioned that the impact of explosives is limited to the pushing effect of the explosion. This agrees with observations of GUBLER (1977) that the impact is limited to the shock wave because N-waves attenuate very fast in fully-wet and soft snowpacks. Nevertheless, other experts observed considerably higher effective ranges for charges placed above the snowpack in wet snow conditions. Differences may result because release mechanisms of wet slab avalanches are more diverse (see chapter 2.3). Thus, fracture initiation potential and fracture propagation may differ considerably according to snowpack conditions and wetness stages. To define effective ranges for surface- and airblasts to release wet slab avalanches, additional research is necessary: Experiments and calculations are necessary to calculate treshold amounts for surface pressures and deformation velocities with regard to the release of different wet slab avalanches.

5.5 Conclusion

The intention of the expert interviews was to find out more about the best timing of control operations and to investigate the most effective release methods for different types of wet snow avalanches.

Best timing for control operations during warm periods with high radiation is expected before radiation and temperature decrease significantly. In fully-wet snowpack conditions fracture propagation may increase just after the last sundown. However, more research work is necessary to find out more about fracture initiation and propagation in fully-wet snowpack conditions just after the last sundown.

Whereas flexible charge placement is very important to release wet loose snow avalanches, high effective ranges are important to improve release success of wet slab avalanches. Defining effective ranges in wet snow conditions is difficult due to different wetness stages of the snowpack. To define effective ranges for surface- and airblasts to release wet slab avalanches, additional research is necessary.

6 Case study

6.1 Introduction

Chapters 2 and 3 introduced the theoretical concepts for wet snow avalanches and artificial avalanche release. The current state of artificial avalanche release in wet snow conditions is investigated in chapter 4: Artificial release of wet snow avalanches is feasible and control operations are frequently performed in many ski areas and above highways or roads. Further knowledge of practitioners was collected through expert interviews to concretize timing of control operations and the effectiveness of release methods with regard to different types of wet snow avalanches. Results are presented in chapter 5. The case study intends to find out more about forecasting of wet snow instabilities and the effectiveness of release methods and to verify previous findings. Therefore, a dataset of weather data, snowpack data and artificially released avalanches is qualitatively and statistically analysed. The general research questions are presented in the following list.

Research questions:

Specify weather and snowpack characteristics to forecast wet snow avalanche activity.

Investigate the most effective release methods and the best charge placement for different types of wet snow avalanches.

6.2 Methods

6.2.1 Location

Weather and avalanche data was provided by the 'Silvretta Bergbahnen AG'. Together with the 'Bergbahnen Samnaun AG' the company is operating a ski area with 44 cableways and lifts and 238 km of ski slopes. The ski area is located in the Silvretta mountains in the inneralpine part of the eastern Alps. Elevation of the ski area is ranging from 1377 m (Ischgl) up to 2864 m (Palinkopf). The ski area connects two villages: Ischgl, in the western part of Tyrol (Austria), and Samnaun, in the eastern part of Grisons (Switzerland). Compared to other non-glacier ski areas, winter seasons last relatively long: The ski area is operating from the end of November to the beginning of May.

According to an analysis of long time weather data in the neighbouring village Galtür (1583 m), the average yearly amount of precipitation is about 1130 mm with a yearly amount of new snow of about 570 cm (ZAMG, 2013). The average yearly temperature on 1583 m sealevel is about 2,7°C (ZAMG, 2013).

Data of artificially released avalanches, snowpack and weather data were obtained from the avalanche control service 'Ischgl-Idalpe'. The avalanche control service is responsible for avalanche safety in the Austrian part of the ski area. They have to control a total of about 475 release points - many of them are also prone to wet snow avalanches. Table 22 shows keyfacts of the avalanche control service 'Ischgl-Idaple' compared to the keyfacts of the survey participants.

Table 22: Keyfacts of the avalanche control service 'Ischgl-Idalpe' and the survey respondents

	Aval. control service Ischgl-Idalpe	Survey (N=50)		
		min.	max.	Ø / #
Operating area				
ski area size [slope km]	238	10	280	71
release points dry snow avalanches [#]	475	2	475	87
release points wet snow avalanches [#]	379	5	379	30
medium sealevel [m]	2384	1750	2750	2235
Control operations				
total amount explosives [kg]	8000	90	10500	2344
amount explosives for wet snow avalanches [kg]	1200	5	1320	261
control operations in wet snow conditions [#]	18	2	27	12
release success rate wet snow avalanches [%]	57	19	90	38

The avalanche control service 'Ischgl-Idalpe' uses different release methods to control avalanches. Two ropeways are installed to serve about 40 release points. A total of 54 autonomous devices are available: 35 Gazex devices and 19 avalanche towers (since 2009). With ropeways and autonomous devices about 22% of the release operations are conducted. Most of the release points are controlled with helicopter or hand delivery. The helicopter is permanently available because a helicopter base is located in the middle of the ski area. Thus, helicopter delivery is by far the most frequently used release method: 55% of the release operations are carried out with helicopter delivery. Hand delivery is also frequently used: 21% of the release operations are conducted by hand delivery of explosives. Mechanical triggering with groomers is occasionally used to control avalanches.

Within the ski area 3 different starting zones were chosen for detailed investigations. Keyfacts of the starting zones are given in table 23. According to the author's observation, wet snow avalanche release mechanisms differ between the three starting zones. Whereas the starting zone Velill is prone to wet loose snow avalanches, the starting zones Maas and Höllkar are prone to wet slab avalanches. Photos of the starting zones and released avalanches are provided in appendix C.

Table 23: Keyfacts of investigated starting zones

	Maas	Velill	Höllkar
Release points and release methods			
total number of release points [#]	24	36	17
release points ropeway [#]	15		7
release points Gazex [#]	6	2	
release points hand, groomer [#]	3		1
release points helicopter only [#]	0	34	9
Terrain characteristics			
release points - min. sealevel [m]	2132	2129	2261
release points - max. sealevel [m]	2308	2776	2547
release points - mean sealevel [m]	2240	2477	2406
release points - mean incline [°]	38	41	35
main aspect	NW	SW	NE

6.2.2 Data

A dataset for 10 winter seasons (1998/99 until 2007/08) was prepared. Weather and snowpack data was obtained from three automatic weather stations located in the ski area of Ischgl: Höllboden (2147 m), Idalpe (2315 m) and Palinkopf (2864 m). Parameters recorded include air temperature, relative humidity, wind velocity and direction, radiation, snow depth and snow temperatures. Details for each weather station are presented in table 24. Dataloggers recorded measured weather and snow parameters in 30 minutes steps for the whole winter season from November to May.

Table 24: Measured weather and snowpack parameters

	Abbrevation	Unit	Measured interval	Höllboden (2147 m)	Idalpe (2315 m)	Palinkopf (2864 m)	Madlein (2907 m)	Pischgraben (2280 m)	Idalpe - study plot (2315 m)
Weather parameters									
air temperature	TA	°C	30 min		X	X		X	
relative humidity	RH	%	30 min		X	X		X	
wind velocity	FF	m/s	30 min		X	X		X	
wind maximum velocity	FFmax	m/s	30 min		X	X		X	
wind direction	DD	°	30 min		X	X		X	
incoming shortwave radiation	ISWR	W/m²	30 min	X			X		
Snowpack parameters									
snow height	HS	cm	30 min	X			X		
snowpack surface temperature	TSS	°C	30 min	X			X		
bottom snowpack temperature	TS0	°C	30 min	X			X		
snowpack temperature 25cm	Ts25	°C	30 min	X			X		
snowpack temperature 50cm	Ts50	°C	30 min	X			X		
snowpack temperature 75cm	Ts75	°C	30 min	X			X		
new snow	HN	cm	24 h						X
cloudiness	CL	%	12 h						X
penetration depth	PD	cm	24 h						X
snow line	SL	m	24 h						X

Two neighbouring weather stations were used to fill data gaps: Pischgraben (2280 m) and Madlein (2907 m). Data of those two weather stations was implemented through correlation functions. Correlation coefficients were calculated separately for each parameter and time span. A topographical map in appendix C shows the location of weather stations and starting zones. The log book of the avalanche control service provides additional weather and snowpack data on a hand measured daily basis. A dataset of penetration depth, snow line, cloudiness and amount of new snow was generated by digitizing manual records of the study plot Idalpe.

Air temperature was calculated for each starting zone. Therefore, a temperature gradient between the weather stations Idalpe and Palinkopf was calculated. According to the calculated lapse rate, a temperature for each starting zone was calculated based on the mean sealevel of the release points of each starting zone. Additionally, the incoming shortwave radiation was calculated for each release point with the 'points solar radiation' tool of ArcGIS Spatial Analyst. The toolset 'solar radiation' calculates the incoming direct and diffuse shortwave radiation based on methods proposed by FU (2000) and FU and RICH (2002). Detailed information on the calculation methods is given in ESRI (2014). The shortwave radiation was calculated for all days with wet snow control operations. Depending on the cloudiness of a given day, the shortwave radiation was calculated for clear (0%≤CL<33%), partly cloudy (33%≤CL<66%) or cloudy sky (66%≤CL≤100%). Hourly radiation was summed up until control operation started on a specific day.

Manual snow profile data was obtained from the avalanche control service. Additional snowprofile data from the neighbouring Samnaun area was taken out of the Swiss snow profile database (observation station TRD). Finally, a set of 174 snow profiles was available for the winter seasons reviewed. Details of the dataset are shown in appendix C. Snow profile data includes information on grain type and size, snow hardness, ram hardness, snow temperature, estimated liquid water content and snowpack stability. Because of different elevations, aspects and time spans of the available snow profiles, no time series could be created for detailed statistical analysis. Thus, snowprofile data was only used to generally characterize snowpack properties for each winter season.

To obtain additional snowpack data, a simulation was performed with the 1-D snow cover model SNOWPACK (BARTELT and LEHNING, 2002; LEHNING et al., 2002a,b). The SNOWPACK model was performed at the station Idalpe (2315 m). Additional input data was taken from the weather stations Höllboden and Palinkopf. The SNOWPACK simulation was performed for a flat slope only. Snow stratigraphy and snow temperatures were obtained through the model output data. Details on model settings, input data and results are given in appendix C.

A dataset for statistical analysis was prepared based on data of weather stations, study plot and SNOWPACK simulations. In addition, starting zone specific temperature and radiation data was implemented into the dataset. Mean, maximum and minimum values as well as sums over 1, 3 and 5 days were calculated for chosen parameters. Details of the final dataset are given in table 25.

Table 25: Weather and snowpack variables

	Abbrevation	Unit	Höllboden (2147 m)	Idalpe (2315 m)	Palinkopf (2864 m)	Maas (Ø 2240 m)	Höllkar (Ø 2406 m)	Velill (Ø 2477 m)
Air temperature	**TA**							
mean daily air temperature	mean TA	°C		X	X	X	X	X
3 day mean TA	3d mean TA	°C		X	X	X	X	X
5 day mean TA	5d mean TA	°C		X	X	X	X	X
minimum daily air temperature	min TA	°C		X	X	X	X	X
3 day sum of min TA	3ds min TA	°C		X	X	X	X	X
5 day sum of min TA	5ds min TA	°C		X	X	X	X	X
maximum daily air temperature	max TA	°C		X	X	X	X	X
3 day sum of max TA	3ds max TA	°C		X	X	X	X	X
5 day sum of max TA	5ds max TA	°C		X	X	X	X	X
max. positive daily air temperature	max TA(+)	°C		X	X	X	X	X
3 day sum of max positive TA	3ds max TA(+)	°C		X	X	X	X	X
5 day sum of max positive TA	5ds max TA(+)	°C		X	X	X	X	X
Relative humidity	**RH**							
mean daily relative humidity	mean RH	%		X	X			
3 day mean RH	3d mean RH	%		X	X			
5 day mean RH	5d mean RH	%		X	X			
Cloudiness	**CL**							
mean cloudiness	mean CL	%		X				
3 day mean CL	3d mean CL	%		X				
5 day mean CL	5d mean CL	%		X				
Snowpack surface temperature	**TSS**							
Minimum snowpack surface temp.	min TSS	°C	X					
3 day min TSS	3d min TSS	°C	X					
6 day min TSS	5d min TSS	°C	X					
Snow height	**HS**							
mean snow height	mean HS	cm	X					
Isothermal portion of snowpack	**IPS**							
mean isothermal portion of snowp.	mean IPS	%	X					
2 day mean IPS	2d mean IPS	%	X					
3 day mean IPS	3d mean IPS	%	X					
5 day mean IPS	5d mean IPS	%	X					
Incoming shortwave radiation	**ISWR**							
maximum incoming shortwave rad.	max ISWR	W/m²	X					
3 day max ISWR	3d max ISWR	W/m²	X					
5 day max ISWR	5d max ISWR	W/m²	X					
daily sum of incoming shortw. rad.	ISWR	W/m²	X			X	X	X
3 day sum of ISWR	3ds ISWR	W/m²	X					
5 day sum of ISWR	5ds ISWR	W/m²	X					
Wind velocity	**FF**							
mean wind velocity	mean FF	m/s		X	X			

Avalanche data was obtained through the database of the avalanche control service. Control operations and release success are documented for each release point in the 'avalanche forecasting and diagnose system (AFADE)'. The AFADE program was developed by KLEEMAYR et al. (2000) and is a forecasting and documentation tool based on the nearest neighbour method. Among other details, the database includes information on release method, charge size, release success, timing of control operation and avalanche size (since 2005/06). Because avalanche sizes are documented only for 3 of the investigated 10 winter seasons, no avalanche activity index was applied in the data analysis. The database does not differentiate between wet and dry snow conditions. To classify wet and dry snow avalanches, the log book of the avalanche control service was used. Finally, a dataset of 81 days with wet snow avalanche control operations and 2237 documented artificial release operations was prepared for further statistical analysis.

6.2.3 Data analysis

Descriptive statistics were used to analyse the general characteristics of each winter with regard to wet snow avalanche activity, temperature trends, amount of snow and general snowpack characteristics. Results were analysed qualitatively.

To find out more about forecasting of wet snow avalanche activity, the dataset of weather, snowpack and avalanche data was statistically analysed. The objective is to find differentiating variables for days with control operations or days with good release success. Days with control operations were compared with previous days and days with good release success were compared with days with no or moderate (<33%) release success.

The avalanche types observed differ considerably among the starting zones Maas, Höllkar and Velill. The release mechanisms of slab and loose snow avalanches are obviously different. Thus, metereological and snowpack parameters were analysed separately for each starting zone. The grouped data was also compared between the starting zones in order to find out differences with regard to the prevailing avalanche type.

Different weather situations provoke wet snow instabilities. Wet snow instabilities during warm periods with high radiation are most common in alpine areas. Rain on snow events and rapid warming after (wet) snowfall are also common triggers. To consider different weather situations, days were grouped according to the amount of precipitation on the day with control operation and on previous days. Details are shown in table 26.

Table 26: Number of days with control operations: grouping according to precipitation

	Abbrevation	All starting zones	Maas	Höllkar	Velill
Precipitation within the last 24h	P24	12	10		
good release success	P24G	5	4	1	1
no or moderate release success	P24N	7	6	3	2
previous day	*P24P*		*7*	*3*	*3*
Precipitation within the last 72h	P72	18	11	5	4
good release success	P72G	10	5	2	4
no or moderate release success	P72N	8	6	3	0
previous days	*P72P*		*9*	*4*	*3*
Precipitation-free periods	PFP	51	22	19	14
good release success	PFPG	33	15	9	7
no or moderate release success	PFPN	18	7	10	7
previous day	*PFPP*		*17*	*15*	*13*

Because of the small sample sizes for days with rain on snow events or precipitation in advance (P24, P72), no further analysis has been carried out. Statistical analysis was focusing on days with control operations in precipitation-free periods. To determine whether or not metereological and snowpack parameters differ among the respective groups, a univariate statistical analysis was performed. The non-parametric Mann-Whitney-U test was applied to analyse groups of data (RASCH et al., 2010b). A level of significance p=0,05 was chosen to decide whether the differences observed were statistically significant. Significant differences are presented in the following chapter. Data distribution was also graphically analysed with box plots. The complete set of box plots is given in appendix C.

The effectiveness of different release methods was investigated by analysing release success rates. To make assumptions for different wet snow avalanche types, release data was analysed separately for different starting zones (Maas, Höllkar, Velill). Descriptive statistics were applied.

Microsoft Excel, statistical software SPSS and the software OriginPro were used to analyse data and to create charts.

6.3 Results

6.3.1 Winter characteristics and wet snow avalanche activity

During the period of 10 winter seasons, 81 days with wet snow control operations were observed with a total of 2237 documented artificial release operations. Temperature trends, amount of snow, snowpack characteristics and avalanche activity for each winter season is shown in figure 55. A detailed graphical analysis for each winter season is provided in appendix C including temperature trends, amount of snow, snowpack temperatures, release operations and release success in the starting zones Maas, Höllkar and Velill.

The peak of wet snow avalanche activity was observed in the season 2002/03. That winter season is characterized by a low snow depth over the whole season and cold temperatures in January and February. Thus, the portion of persistent grains also reached the peak in that season. Pronounced weak snowpack basement was prevalent. Because of relatively high temperatures in March and April, the snowpack rapidly turned isothermal, which resulted in several avalanche cycles during the spring season. Details are given in figure 55.

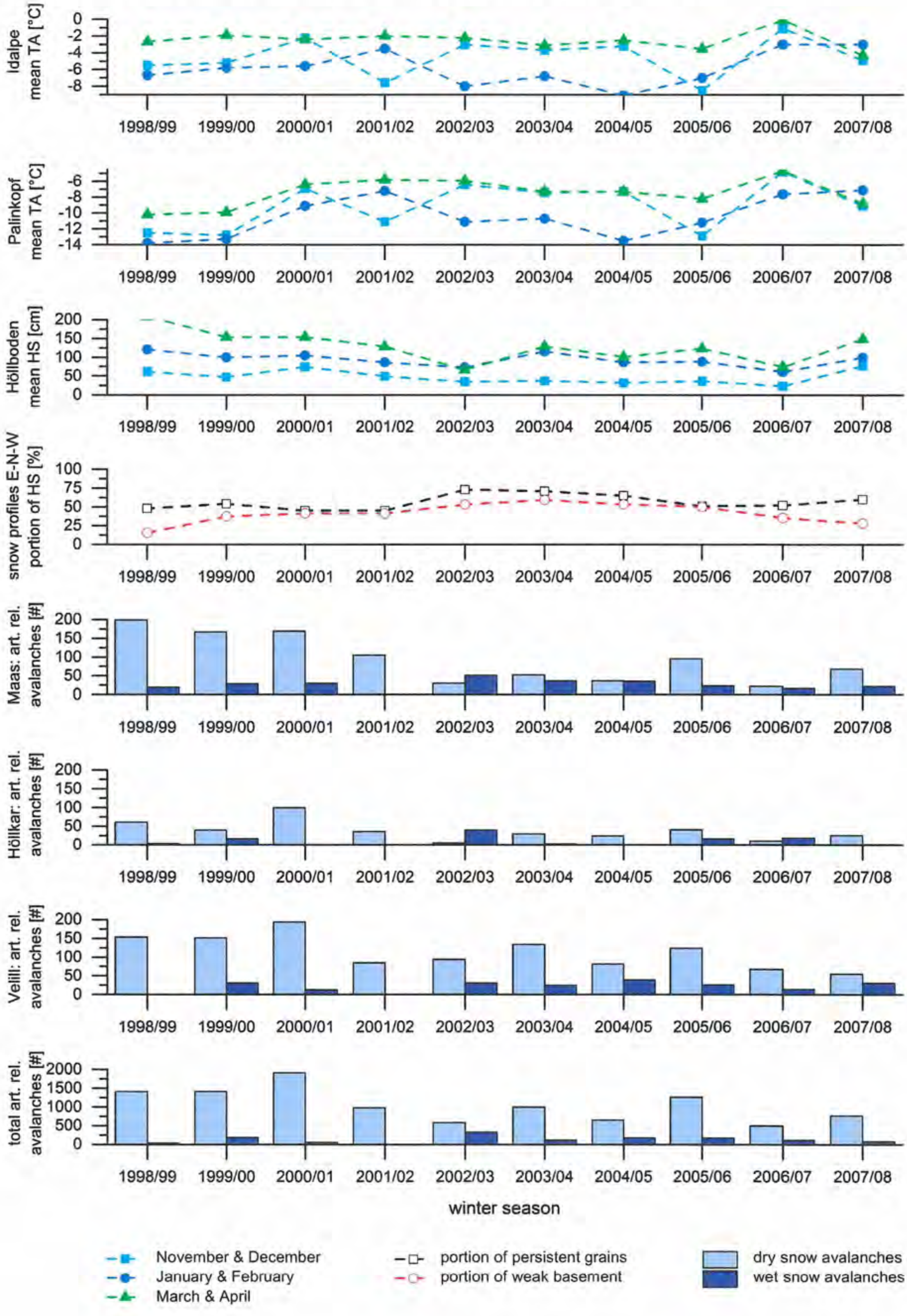
A better snowpack basement was present in winters with less wet snow avalanche activity. According to the SNOWPACK simulation, the snow cover (flat slope, 2300 m) usually gets isothermal between mid of March and mid of April (see appendix C). There is a tendency that the earlier the snowpack gets isothermal, the more days with control operations and the more wet snow avalanche activity is observed. No obvious relation exists between the number of dry snow avalanches released and the number of wet snow avalanches released.

Warm periods with high radiation are the most common trigger for wet snow instabilities. On average, rain on snow events are observed once a season. Because of the high elevation, rain on snow events are rare in the starting zones Höllkar and Velill, whereas rain on snow events are sometimes observed in the starting zone Maas. Wet snow instabilities provoked by warming after snowfall are observed twice a season, on average.

According to personal observations, the starting zones Maas and Höllkar are prone to wet slab avalanches and the starting zone Velill is prone to wet loose snow avalanches. According to the graphical analysis (figure C.11 - figure C.20), often several control operations per avalanche cycle are necessary to empty the starting zone Maas and Höllkar, whereas the starting zone Velill is usually emptied with one control operation per avalanche cycle.

In the starting zone Maas often two or more than two avalanche cycles per season provoke control operations. The first cycle is often related to the first serious wetting of the snowpack, whereas the snowpack seems to be fully-wet during the follow-up cycles. A maximum of one or two avalanche cycles per winter season is observed in the starting zone Höllkar. Because of the higher elevation of the starting zone Höllkar, the first avalanche cycle is usually observed later in the season. Whether the snowpack is transitional or fully-wet in the starting zone Höllkar during the first cycle of avalanche activity cannot be determined with the present data.

Figure 55: Characteristics of investigated winter seasons (1998/99 - 2007/08)



6.3.2 Forecasting wet snow avalanche activity

To find out characteristics of days with control operations and days with good release success, weather and snowpack data were analysed for the starting zones Maas, Höllkar and Velill. The investigated dataset of variables is shown in table 25. Significant results of the statistical analysis (Mann-Whitney-U test) are given in table 27. Data distribution was also graphically analysed using box plots. The complete set of box plots is given in appendix C.

Table 27: Significant differences between PFPN & PFPG / PFP & PFPP

Variable	Unit	Station	Maas: PFPG vs. PFPN	Maas: PFP vs. PFPP	Höllkar: PFPG vs. PFPN	Höllkar: PFP vs. PFPP	Velill: PFPG vs. PFPN	Velill: PFP vs. PFPP
5d mean TA	°C	Idalpe						*
3ds min TA	°C	Idalpe		*				
3ds min TA	°C	starting zone		*				
5ds min TA	°C	starting zone						*
5ds max TA(+)	°C	Palinkopf			*			
5d mean RH	%	Idalpe					*	
5d min TSS	°C	Höllboden	*					
mean IPS	%	Höllboden	*					
2d mean IPS	%	Höllboden	*					
3d mean IPS	%	Höllboden	*					
5d mean IPS	%	Höllboden	*					
ISWR	W/m²	starting zone					*	
max ISWR	W/m²	Höllboden					*	
3d max ISWR	W/m²	Höllboden					*	
5d max ISWR	W/m²	Höllboden					*	

Significant differences are maked by: $p \leq 0,001$ = ***, $p \leq 0,01$ = **, $p \leq 0,05$ = * .

In the starting zone Höllkar weather and snowpack data do not differ significantly between days with control operations (PFP) and previous days (PFPP). In the starting zone Maas the 3-day sum of minimum temperatures at the weather station Idaple and the calculated 3-day sum of minimum temperatures for the starting zone are significantly higher on days with control operations. In the starting zone Velill the 5-day mean temperature at the weather station Idaple and the calculated 5-day sum of minimum temperatures for the starting zone are significantly higher on days with control operations. All other variables do not vary significantly between days with control operations and previous days in the starting zone Maas and Velill. Thus, an appropriate forecasting for days with control operations based on the available dataset and univariate statistical methods is not possible.

Weather and snowpack data for days with good release success (PFPG) and days with no or moderate release success (PFPN) only differ slightly within the starting zones. In the starting zone Velill radiation is significantly higher and the 5-day mean of relative humidity is significantly lower on days with good release success. In the starting zone Höllkar only the 5-day sum of maximum positive air temperatures is significantly higher on days with good release success. The simulated isothermal portion of the snowpack and the 5-day minimum surface temperature at the weather station Höllboden are significantly higher for days with good release success in the starting zone Maas. All other variables do not vary significantly between days with good release success and days with no or moderate release success. Based on the limited set of significantly tested variables, it is hardly possible to make an appropriate forecast for days with good release success. Significantly tested variables differ between the starting zones: Whereas radiation seems to be related to the release success in the starting zone Velill, snowpack characteristics seem to be more important for forecasting release success in the starting zone Maas.

Differences between starting zones are further analysed by comparing weather characteristics of days with control operations and days with good release success between the starting zones Maas, Höllkar and Velill. The dataset investigated includes starting zone specific temperature and radiation variables and general weather parameters (RH, CL, FF) from table 25. Significant results of the statistical analysis (Mann-Whitney-U test) are given in table 28. Data distribution was also graphically analysed using box plots. The complete set of box plots is given in appendix C.

The starting zones Maas and Höllkar are both prone to wet slab avalanches. The amount of radiation input on days with control operations and on days with good release success is significantly higher in the starting zone Höllkar. All other variables do not vary significantly between those two starting zones. Wet loose snow avalanches are usually triggered in the starting zone Velill. Multiple variables differ significantly between the starting zone Velill compared to the other two starting zones: The starting zone specific temperature is generally higher on days with control operations and on days with good release success in the starting zones Maas and Höllkar - especially when variables also include temperatures of previous days. Relative humidity and cloudiness factor are also higher in the starting zones Maas and Höllkar - especially on days with good release success. Starting zone specific radiation is significantly higher in the starting zone Velill than in the starting zone Maas. Compared to the starting zone Höllkar, the radiation input is not significantly different in the starting zone Velill.

Comparing weather parameters for days with control operations and days with good release success shows that avalanche forecasting based on weather data is strongly starting zone specific.

Table 28: Significant differences of weather variables between starting zones

Variable	Unit	Station	PFPG: Maas vs. Höllkar	PFPG: Maas vs. Velill	PFPG: Höllkar vs. Velill	PFP: Maas vs. Höllkar	PFP: Maas vs. Velill	PFP: Höllkar vs. Velill
mean TA	°C	starting zone		*			*	**
3d mean TA	°C	starting zone		**	*		***	***
3d mean TA	°C	starting zone		***	**		***	***
min TA	°C	starting zone					*	**
3ds min TA	°C	starting zone		**			***	***
5ds min TA	°C	starting zone		**	*		***	***
max TA	°C	starting zone		*			**	**
3ds max TA	°C	starting zone		***	*		***	***
5ds max TA	°C	starting zone		***	**		***	***
max TA(+)	°C	starting zone		*			*	**
3ds max TA(+)	°C	starting zone		***	*		***	***
5ds max TA(+)	°C	starting zone		***	**		***	***
ISWR	W/m²	starting zone	**	**		***	***	
mean RH	%	Idalpe		*	**		*	**
3d mean RH	%	Idalpe		*	**			***
5d mean RH	%	Idalpe		*	**			***
mean RH	%	Palinkopf		*	**		*	**
3d mean RH	%	Palinkopf		**	**		*	***
5d mean RH	%	Palinkopf		**	**			***
mean CL	%	Idalpe		**	**		*	*
3d mean CL	%	Idalpe		**	**		*	*
5d mean CL	%	Idalpe		**	**			

Significant differences are maked by: $p \leq 0{,}001$ = ***, $p \leq 0{,}01$ = **, $p \leq 0{,}05$ = * .

6.3.3 Effectiveness of release methods

Helicopter charging is by far the most widely applied release method to trigger wet snow avalanches in the ski area investigated. Ropeways are slightly more often used in wet snow conditions than in dry snow conditions. Overall, ropeways do have the best release success rate in wet snow conditions. Gazex is less frequently used to release wet snow avalanches. Hand charging and groomers are rarely used in wet snow conditions. Details are given in table 29.

Table 29: Applied release methods, success rates and charge sizes

Release method	Release operations in dry snow conditions	Average charge size in dry snow conditions	Release operations in wet snow conditions	Average charge size in wet snow conditions	Release success rate in wet snow conditions
Starting zone: Maas					
hand delivery	3,2%	4,9 kg	0,9%	8,8 kg	100,0%
helicopter charging	13,7%	4,6 kg	47,0%	5,0 kg	46,0%
ropeway	55,6%	4,9 kg	36,5%	9,1 kg	79,9%
groomer	0,1%	-	0,4%	-	100,0%
Gazex	27,5%	-	15,1%	-	50,0%
total starting zone	# 1459	4,9 kg	# 449	6,6 kg	59,7%
Starting zone: Höllkar					
hand delivery	14,0%	5,8 kg	-	-	-
helicopter charging	49,8%	4,9 kg	88,7%	7,2 kg	42,6%
ropeway	34,0%	8,1 kg	10,8%	14,8 kg	58,3%
groomer	2,2%	-	0,5%	-	100,0%
Gazex	-	-	-	-	-
total starting zone	# 636	6,1 kg	# 222	8,1 kg	44,6%
Starting zone: Velill					
hand delivery	1,3%	5,5 kg	-	-	-
helicopter charging	86,9%	5,0 kg	97,3%	5,8 kg	64,7%
ropeway	-	-	-	-	-
groomer	0,3%	-	-	-	-
Gazexx	11,5%	-	2,7%	-	33,3%
total starting zone	# 1722	5,0 kg	# 332	5,8 kg	63,9%
All starting zones					
hand delivery	24,0%	5,1 kg	1,8%	6,3 kg	52,5%
helicopter charging	51,6%	4,8 kg	82,0%	5,4 kg	54,0%
ropeway	7,2%	5,5 kg	8,7%	9,7 kg	77,3%
groomer	1,2%	-	1,3%	-	96,6%
Gazex	16,0%	-	6,3%	-	61,4%
total starting zone	# 16321	5,0 kg	# 2237	5,8 kg	57,0%

Compared to the other starting zones investigated, control operations in the starting zone Velill do have the best release success rate. The starting zone Velill is prone to wet loose snow avalanches, whereas the starting zones Maas and Höllkar are prone to wet slabs. The release success rate in the starting zone Maas is about average. However, the success rate in the starting zone Höllkar is considerably lower.

In the starting zone Maas different release methods are applied in wet snow conditions. Helicopter and ropeway delivery are most frequently used. The helicopter is used more frequently than in dry snow conditions, whereas the ropeway is used less frequently. Charge sizes of about 5 kg are used in dry snow conditions. With ropeway delivery charge sizes are nearly doubled in wet snow conditions (~9 kg). For helicopter delivery the applied charge sizes are only slightly larger than 5 kg. Ropeway delivery has a considerably higher release success rate than helicopter charging in the starting zone Maas. Gazex devices are sometimes used in the starting zone Maas. Their release success rate is below average in wet snow conditions. In wet snow conditions Gazex devices are less frequently used in the starting zone Maas compared to dry snow conditions.

Helicopter and ropeway are used to release wet snow avalanches in the starting zone Höllkar. However, the helicopter is by far more frequently used in wet snow conditions than ropeway delivery. Compared to dry snow conditions, larger charge sizes are used in wet snow conditions: For ropeway delivery average charge sizes of about 15 kg are used, for helicopter delivery average charge sizes of about 7 kg are used to release wet snow avalanches. Like in the starting zone Maas, release success rate of ropeway delivery is higher than the success rate of helicopter delivery. Thus, surface- or airblasts with larger charges seem to be more effective to release wet slab avalanches.

Gazex devices installed in the starting zone Velill are mostly used for test releases. Thus, their release success rate is lower than the success rate of helicopter charging in the same starting zone. The helicopter allows flexible charge placement and seems to be an appropriate release method to release wet loose snow avalanches in the starting zone Velill. The average charge size applied in wet snow conditions is only slightly higher than in dry snow conditions.

6.4 Discussion

6.4.1 Forecasting wet snow avalanche activity

The case study agrees with the survey results: In the ski area investigated most of the wet snow avalanches are triggered during precipitation-free periods with high radiation and high temperatures in March and April.

Experts observed wet slab avalanches in fully-wetted snowpacks that have already undergone wet snow metamorphism and transitional snowpacks during the first serious wetting. According to the case study, several wet snow avalanche cycles in fully-wet and transitional snowpacks are observed in the starting zone Maas. In the starting zone Höllkar usually only one cycle is observed. Whether the snowpack is transitional or fully-wet in the starting zone Höllkar cannot be determined with the present data. Frequently observed secondary (and even remote) releases and sharp fracture lines (see figure C.38) are indicators for transitional wet slabs.

Prediction of wet snow instabilities is difficult during typical spring weather conditions. It is not possible to forecast days with control operations or days with good release success based on the investigated dataset and univariate statistical methods. Results agree with previous findings of SKORIC (2013) and MITTERER et al. (2011) that 'forecasting of wet snow avalanches based only on meteorological parameters has proven unsuccessful.' Even if some variables were found to significantly differ, they are more an indicator than a discrimination factor. Thus, findings agree with TRAUTMAN (2008): 'Experiences and research have shown that monitoring air temperature is only partially useful when forecasting wet snow avalanches' because of overlapping data ranges for avalanche and non avalanche days.

However, statistical analysis proved that avalanche forecasting based on weather data is strongly starting zone specific. The starting zones investigated differ with regard to prevailing snowpack conditions, sealevel and aspect. According to the expert interviews and investigations by TECHEL (2008, 2010) and MITTERER (2012), the necessary amount of liquid water to provoke wet snow instabilities on a given day depends on the snowpack structure and wetness stage. Thus, snowpack characteristics have to be implemented and multivariate statistical methods have to be applied in order to improve forecasting results. Radiation income and temperatures differ according to aspect, slope and elevation. Thus, the energy balance would be a more appropriate parameter than single radiation and temperature parameters to forecast wet snow avalanche activity on a given slope. MITTERER and SCHWEIZER (2013a) agree: Calculated energy balance showed up as best predictors for wet snow instability. According to the experts' opinion and literature research, the release type of a wet snow avalanche depends on the snowpack structure. The case study also showed that investigated weather data differs significantly according to the release type. Thus, further investigations on wet snow avalanche forecasting should differentiate between wet loose and wet slab avalanches and take into consideration the energy balance, snowpack structure and wetness stage.

6.4.2 Effectiveness of release methods

The starting zone Velill is prone to wet loose snow avalanches. Most of the release operations are conducted with helicopter delivery. Even if charges are fired within the snowpack and average charge sizes are used, the release success rate is above average. This confirms previous findings that flexible charge placement is more important than optimizing the effective range to release wet loose snow avalanches.

The staring zones Maas and Höllkar are prone to wet slab avalanches. Ropeways are often used to release wet slab avalanches. Bigger charge sizes are applied for ropeway delivery. The release success rate of ropeway delivery with bigger charge sizes is well above average and considerably higher than the release success rate of helicopter delivery in the starting zones Maas and Höllkar. Thus, previous findings are confirmed that charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches in order to maximize the effective range.

Even if bigger charges are used, the effective range in wet snow conditions is limited compared to dry snow conditions. Thus, additional release points have to be triggered compared to dry snow conditions. Usually, preinstalled ropeway or autonomous devices only cover release points in dry snow conditions. Thus, flexible devices are necessary to serve additional release points in wet snow conditions. Therefore, helicopter delivery is frequently applied in the investigated ski area even if release success rate for wet slab avalanches is below average.

Gazex devices are less frequently used in wet snow conditions. All in all, the release success rate is about average. Autonomous devices may be especially suitable for test releases. Hand charging is only rarely used in wet snow conditions because a helicopter is permanently available and weather conditions usually do not limit helicopter operations. Mechanical triggering with groomers is also rarely used because only a limited number of release points can be reached.

The release success rate of wet loose snow avalanches in the investigated starting zones is significantly higher than the release success rate of wet slab avalanches. Often several control operations per avalanche cycle are necessary to empty the starting zone Maas and Höllkar, whereas the starting zone Velill is usually emptied with one control operation per avalanche cycle.

6.5 Conclusion

The intention of the case study was to find out more about weather and snowpack characteristics to forecast wet snow avalanche activity, to investigate the effectiveness of different release methods and to verify previous findings. Therefore, a dataset of weather data, snowpack data and data on artificially released avalanches was qualitatively and statistically analysed.

Forecasting wet snow avalanche activity and timing of control operations is difficult. The necessary amount of liquid water to provoke wet snow instabilities on a given day depends on the snowpack structure and wetness stage. The melt water production is mainly influenced through the energy balance and the structure of the uppermost snowpack layers. According to the snowpack structure, different release types may result. Thus, further investigations on wet snow avalanche forecasting should differentiate between wet loose and wet slab avalanches and take into consideration the energy balance, snowpack structure and wetness stage.

Effectiveness of different release methods has been analysed. Previous findings can be confirmed: Whereas flexible charge placement is very important to release wet loose snow avalanches, high effective ranges are important to improve release success of wet slab avalanches. However, more research work is necessary to find out more about effective ranges of surface- and airblasts in wet snow conditions.

7 Summary and conclusion

7.1 Summary

In chapter 1.1 the general research questions were presented. The most important results are summarized in this chapter.

Assess the current state of artificial release of wet snow avalanches in ski areas and above highways / roads.

The current state of artificial release of wet snow avalanches was investigated through a survey on avalanche control services in Austria, Switzerland and South Tyrol (Italy). About 64% of the responding avalanche control services (N=78) do have experience in artificial release of wet snow avalanches. Most of the experienced respondents are primarily responsible for the avalanche safety in ski areas (47), only few respondents are exclusively responsible for the avalanche safety of highways and pass roads (3).

Controlling wet snow avalanches is common practice in the Austrian and Swiss Alps at elevations above 1500 m. Release zones are mostly situated in southerly slopes from 2000 m to 2500 m. Overall, about one third of the total number of release points is prone to wet snow avalanches. The respondents control between 2 (minimum) and 379 (maximum) release points for wet snow avalanches in their operating area. On average, avalanche control services use about 230 kg of explosives per season (13% of total amount) to control wet snow avalanches. Whereas some avalanche control services apply only a small amount of explosives, there are also some respondents who dissipate up to 1,2 tons of explosives per season to release wet snow avalanches.

According to the survey, control operations for wet snow avalanches in November, December and January are an exception. The first control operations are generally conducted in February. Peak time for control operations is in April: The participating avalanche control services are running over 200 control operations in that month, on average, more than 4 control operations each. Almost as many operations are conducted in March with nearly 180 control operations. In May and June control operations are mainly done for the opening of alpine pass roads and in glacier ski areas.

Determining typical weather patterns causing wet snow instabilities and leading to control operations for wet snow avalanches. Specify the timing for control operations.

Wet snow avalanches are mostly triggered during precipitation-free periods with high radiation and high temperatures in March and April: According to the survey, almost all avalanche control services try to release wet snow avalanches during warm spring periods. Rain on snow events also seem to be a common trigger: Many survey respondents state that, at least sometimes, rain on snow events are leading to control operations. Wet snowfall and rapid warming after snowfall are less frequent triggers for control operations.

Forecasting of wet snow instabilities is difficult during typical spring weather conditions. Control operations during warm periods with high radiation are foreseeable on the morning of the specific day at the earliest. Most experts decide whether or not to start a control operation only a few hours before. According to the experts, instabilities through rain on snow events are more predictable, but rain on snow events are observed less frequently.

The experts' decision whether or not to start a control operation is mostly based on the current weather conditions, on signs of instability and on test releases. Survey participants ranked snowpack observations and automatic weather stations as very important information sources to forecast wet snow avalanche activity.

Most experts believe that the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation. Previous studies also reveal that strength of snow decreases exponentially or abruptly at the transition from pendular to funicular regime or at a lower liquid water content if persistent weak layers are present. Thus, the best timing for control operations during warm periods with high radiation is just before radiation and temperature decrease significantly. In transitional snowpack conditions all experts agree that release success decreases suddenly when the slope gets covered by the shadow. However, in fully-wet snowpack conditions some experts report increased release success or increased fracture propagation when control operations were conducted just after the last sundown. But there are also some experts who observed a sudden decrease of release success in fully-wet snowpack conditions just after the last sundown. More research work is necessary to find out more about fracture initiation and propagation in fully-wet snowpack conditions just after the last sundown.

Evaluate the effectiveness of different release methods with regard to different types of wet snow avalanches.

In wet snow conditions the effective range for charges fired within the snowpack is limited to the area around the crater zone. The experts' estimation for effective ranges of standard charges (1,5 to 2,5 kg) placed above the snowpack differs considerably: The effective range is estimated to be between 8,5 meters and 57 meters with a median of 20 meters radius. Compared to dry snow conditions, the effective range in wet snow conditions is expected to be reduced by a factor of between 10% and 66%. More research work is necessary to find out details about effective ranges of surface- and airblasts in wet snow conditions.

According to the survey, wet loose snow avalanches are more frequently triggered than wet slab avalanches. Experts' observations agree with survey results: Wet slabs are also triggered in wet snow conditions but by far less frequently than wet loose snow avalanches. The expected avalanche type depends on snowpack properties. To release wet loose snow avalanches, flexible selection of release points is more important than optimizing the effective range when choosing the release method. Systematic triggering of wet loose snow avalanches in order to enforce spreading, snow entrainment and secondary releases can help to empty a starting zone efficiently. Like in dry snow conditions, charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches. However, more charges are needed because of the reduced effective range in wet snow conditions.

As in dry snow conditions, charge placement is mostly done from helicopter or by hand. Compared to the artificial release of dry snow avalanches, release methods with flexible charge placement are more frequently used, whereas autonomous and projectile devices are less frequently used in wet snow conditions. Throughout a case study, the release success rate of Gazex, helicopter, hand and ropeway delivery was analysed. Overall, ropeways showed by far the best release success rate (77%) - especially with regard to wet slab avalanches. Helicopter delivery is most frequently used in the area investigated: For the release of wet loose snow avalanches helicopter charging has a quite good release success rate (69%).

Analyse if artificial release is an appropriate mitigation measure for wet snow avalanches and determine the limitations.

According to the survey, control operations are frequently carried out in many ski areas and above highways or roads. The release success rate in wet snow avalanche control operations is generally lower than in dry snow conditions: According to the survey, the average release success rate in dry snow conditions is about 60% (N=48). The average release success rate in wet snow conditions is only about 38% (N=47). However, about 24% of the respondents reach a success rate higher than 60% also in wet snow conditions. Defining reasons of success by analysing survey results is hardly possible. However, personal experience, knowledge and accurate observation of snowpack conditions might increase release success. Possibly, release success rates depend on snow climates and their specific snowpack conditions: Avalanche control services with a success rate higher than 70% exclusively operate in inneralpine areas.

The reasons for negative release success are often connected with the difficult timing of control operations. For decision making, negative release results in dry snow conditions should be distinguished from those in wet snow conditions: Whereas the stability of dry snowpacks usually improves with time after precipitation events (of course this is not valid for persistent weak layers), the stability of wet snowpacks generally decreases with time of radiation and warming. Therefore, negative release results only grant stability for a limited time frame. Decision making on positive release results and empty starting zones is, therefore, much easier. According to the case study, often several succeeding control operations are necessary to completely empty bigger starting zones.

About two thirds of the avalanche control services can reduce closure times significantly through artificial release of wet snow avalanches. Those who cannot reduce closure times do have a significantly lower release success rate or they might generally prefer closure because of the damage potential of wet snow avalanches or they might have additional problems with full depth glide snow avalanches.

Artificial release of wet snow avalanches is feasible and helps to reduce closure times significantly in many areas. As well as in dry snow conditions, limitations through closure times and damage potential have to be considered within the design process of safety concepts.

7.2 Practical implications

Artificial release of wet snow avalanches is possible and practiced by many avalanche control services within Austria and Switzerland. The following chapter summarizes the most important results of the study for practical implications.

7.2.1 Wet snow stability assessment

Snowpack conditions

During warm weather periods with high radiation, the snowpack has to be in a basic disposition in order to develop wet snow instabilities on a given day. The basic disposition is characterized by already isothermal, moist or wet snowpack (layers) and / or potential weak layers, for example:

- Isothermal snowpack (layers).
- Moist or wet snowpack (layers), for details see figure 2.
- Shining snow surface.
- No or thin crust in the morning, caused by poor radiant emittance.
- Weak snowpack basement (persistent grains).
- Warming influence of the ground on the snowpack basement.

The wetness stage of the snowpack may be less important for wet snow instabilities caused by rain on snow events because a high amount of liquid water can rapidly alter the snowpack temperature and wetness stage.

Liquid water content

The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure. If snowpack stability is close to critical before first (or repeated) wetting occurs, not much liquid water is required for weak snowpack layers to become unstable. If the snowpack is stable, a high amount of liquid water has to be concentrated in order to develop wet snow instabilities (see figure 6).

The available amount of liquid water depends on weather parameters. During warm periods with high radiation, liquid water is produced through melting upper snowpack layers. The following weather parameters support melt water production: foggy radiation weather conditions, intense radiation, high minimum and maximum temperatures, high relative humidity, overcast nights and rapid warming after new snow. However, there are different opinions with regard to the influence of wind: Foehn may provoke wet snow instabilities through wetting of the upper snowpack layers or prohibit wet snow instabilities through taking away humidity from the snowpack; cold winds may or may not have a stabilizing effect on the snowpack. During rain on snow events additional liquid water is provided through direct water input by precipitation (wet snowfall, rain). In addition, rain increases the melting rate in the upper snowpack layers due to the release of latent heat - especially in new snow layers (rising snow line during a precipitation event) - and provides additional weight on the snowpack.

Test releases & signs of instability

Test releases and signs of instability are valuable information to decide whether or not to start a control operation. When wet snow instabilities develop, signs of instability may be observed, like for example:

- High penetration depth (boot, ski, pole).
- Tumbling snowballs on the snowpack surface.
- Natural avalanches.

Type of wet snow avalanche

The release type of a wet snow avalanche depends on the snowpack structure. Wet loose snow avalanches form through uniform wetting of the upper snowpack layers or through wetting of the whole (shallow) snowpack (homogeneous layers). The whole snowpack is fully-wet (type 4 wetness classification, see figure 2), very soft and has only very low ram resistance, comparable to type 1 of ram hardness classification (WIESINGER and SCHWEIZER, 2000). If only the upper snowpack layers consist of very soft and wet grains (type 2 wetness classification), surface wet loose snow avalanches develop. The upper layers may consist of wet snow grains formed by melt-freeze metamorphism or immediately wetted new snow. Harder and more stable snowpack layers beneath impede the development of full depth avalanches.

Wet slab avalanches develop in snowpacks with weak basal layers and snowpacks with persistent weak layers, capillary barriers or crusts. Additionally, slab like characteristics are necessary for fracture propagation. Wet slab avalanches can be observed in fully-wetted snowpacks (type 4 wetness classification) that have already undergone wet snow metamorphism, in transitional snowpacks (type 3 wetness classification) during the first serious wetting or after new snow on wet snowpack layers (type 5 of wetness classification). The fracture line of fully-wet slab avalanches is usually irregular and scraggly. Usually, fracture propagation potential of wet slab avalanches is low. Thus, the fracture line has only a limited width. Sharp fracture lines are connected with transitional wet slabs. Fracture propagation potential for transitional wet slabs is generally higher - experts reported scattered released avalanches with a fracture line width of 150 m to 300 m.

7.2.2 Conducting control operations in wet snow conditions

Effective ranges in wet snow conditions

In wet snow conditions the effective range for charges fired within the snowpack is limited to the area around the crater zone. Compared to dry snow conditions, the effective range for surface- or airblasts is expected to be reduced by a factor of between 10% and 66% (see figure 54). The effective range may vary according to the wetness stage, the hardness and thickness of the overlying slab.

Charge placement in wet snow conditions

Wet loose snow avalanches: Completely wetted areas and steep parts of the slope should be chosen for charge placement. Within the starting zone most-wetted areas are usually found at places with shallow snowpacks. The steeper, the easier it is to release a wet loose snow avalanche. Steep parts of the starting zone usually also get more radiation. In rocky starting zones the snowpack is often very wet nearby and around rocks. The aspect of the chosen release points is also very important: Often different aspects are available within a starting zone especially in structured terrain. Thus, it is important to accurately choose the release point according to its aspect in order to hit the most-wetted place within the starting zone.

Wet slab avalanches: Like in dry snow conditions, charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches in order to maximize the effective range. According to the experts, charge placement is similar to dry snow conditions (see STOFFEL, 2001; MCCLUNG and SCHAERER, 2006).

General remarks: Generally, more charges are needed because of the reduced effective range in wet snow conditions. Within big starting zones it is possible that conditions change according to the sealevel. The uppermost part may not be wet enough, but lower parts may be ready for release. Systematic triggering of wet loose snow avalanches in order to enforce spreading, snow entrainment and secondary releases can help to empty a starting zone efficiently.

Suitability and effectiveness of release methods

The general efficiency and suitability of different release methods for wet loose snow and wet slab avalanches is estimated in table 31. Effective range, charge placement and duration are analysed for each method. Weighting of the characteristics is differentiated according to the avalanche type (table 30). Usually, one or only few release methods are available for a given release point. Thus, options are limited when choosing release methods for practical purpose.

Table 30: Weighting of release method characteristics

	Wet loose snow avalanches	Wet slab avalanches
Effective range		
charge size	15%	30%
charge position	15%	30%
Charge placement		
flexible charge placement	50%	20%
placement accuracy	10%	10%
Duration		
duration	10%	10%

Table 31: Suitability and effectiveness of release methods in wet snow conditions

	Rating charge size	Rating charge position	Rating flex. charge placement	Rating placement accuracy	Rating duration	Total weighted percentage for wet loose snow avalanches	**Suitability wet loose snow avalanches**	Total weighted percentage for wet slab avalanches	**Suitability wet slab avalanches**
Explosives - hand delivery									
with / without rope	100%	0%	75%	100%	0%	63%	+	55%	~
out of cableway	100%	50%	50%	50%	50%	58%	~	65%	+
helicopter charging	100%	0%	100%	50%	100%	80%	++	65%	+
Explosives - ropeways									
ropeway (motorized)	100%	100%	50%	100%	0%	65%	+	80%	++
Explosives - towers									
avalanche guard (blaster box)	50%	0%	25%	50%	100%	30%	-	30%	-
avalanche tower (Inauen Schätti)	50%	100%	0%	100%	100%	43%	~	65%	+
avalanche tower (Wyssen)	50%	100%	0%	100%	100%	43%	~	65%	+
Explosives - projectile delivery									
avalanche pipe	0%	0%	50%	0%	0%	25%	-	10%	--
avalancheur (2phase liquid explosives)	0%	50%	50%	0%	0%	33%	-	25%	-
mortar (military; TNT)[2]	0%	50%	50%	0%	0%	33%	-	25%	-
rocket-tube (military; Oktasit)[2]	0%	50%	50%	0%	0%	33%	-	25%	-
Gas exploders									
Gazex	50%	100%	0%	100%	100%	43%	~	65%	+
Daisy Bell	25%	100%	100%	50%	100%	84%	++	73%	+
Mechanical triggers									
groomer	100%	100%	50%	100%	0%	65%	+	80%	++
ski cutting[1]	100%	100%	75%	100%	0%	78%	+	84%	++

[1] small starting zones only [2] military weapons are not permitted in Austria

7.3 Recommendations for future research

Wet snow mechanics and wet snow avalanche predicition are not well understood yet. Future research is necessary to improve knowledge of wet snow avalanches in general. Among others, MITTERER (2013) and TECHEL (2010) give future research perspectives. Future findings on wet snow avalanches in general will also help to improve knowledge of artificial avalanche release in wet snow conditions. With regard to artificial release of wet snow avalanches, the present study leads to the following perspectives for future investigations:

a. Forecasting of wet snow avalanche activity during typical spring periods with high radiation and warm temperature is difficult. The necessary amount of liquid water to provoke wet snow instabilities on a given day depends on the snowpack structure and wetness stage. Melt water production is mainly influenced through the energy balance and the structure of the uppermost snowpack layers. According to the snowpack structure, different release types may result. Thus, further investigations on wet snow avalanche forecasting should differentiate between wet loose and wet slab avalanches and take into consideration the energy balance, snowpack structure and wetness stage.

b. Best timing for control operations during warm periods with high radiation is expected before radiation and temperature decrease significantly. In fully-wet snowpack conditions fracture propagation may increase just after the last sundown. However, more research work is necessary to find out more about fracture initiation and propagation in fully-wet snowpack conditions just after the last sundown.

c. Whereas flexible charge placement is very important to release wet loose snow avalanches, high effective ranges are important to improve release success for wet slab avalanches. Defining effective ranges in wet snow conditions is difficult. The attenuation of the explosives' shock-, stress- and N-waves depends on the wetness and hardness of snowpack (layers) and the thickness of the overlying slab. Furthermore, the treshold stress value for fracture initiation may also vary according to snowpack structure, wetness stage and predominant slab release mechanism. Thus, effective ranges for surface- and airblasts may differ according to the wetness stage and structure of the snowpack: In more transitional snowpacks a higher effective range is expected than in fully-wet snowpack conditions. However, more research work is necessary to find out more about effective ranges of surface- and airblasts in wet snow conditions.

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Appendix A: Questionnaire-based survey

Table A.1: Test results for chapter '4.3.1 Release zones and terrain characteristics'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: souherly_exposed			Yes N=39	No N=11	
release_points_wsa>30	binary {0, 1}	Fisher exact	0,36	0,00	0,022
remote_slab_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,56	0,73	0,005
remote_slab_wsa_rarely	binary {0, 1}	Fisher exact	0,18	0,73	0,001
remote_slab_wsa_no	binary {0, 1}	Fisher exact	0,64	0,27	0,042
slope_gramineous_many&some	binary {0, 1}	Fisher exact	0,68	0,37	0,034
info_weather_station_very_important	binary {0, 1}	Fisher exact	0,74	0,36	0,030
weather_radiation_important	binary {0, 1}	Fisher exact	0,03	0,27	0,029
rain_on_snow_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,77	1,36	0,043
rain_on_snow_rarely	binary {0, 1}	Fisher exact	0,08	0,45	0,009
#_release_points_wsa	metric [#]	Mann Whitney U	35,90	10,90	0,011
info_class3_index	metric {Σ i(0..3)}	Mann Whitney U	2,54	1,90	0,027
control_operations_mar	metric [#]	Mann Whitney U	4,46	2,27	0,032
#_control_operations	metric [#]	Mann Whitney U	13,34	7,27	0,007
Group variable: east			Yes N=25	No N=25	
loose_wsa_often	binary {0, 1}	Fisher exact	0,44	0,12	0,025
Group variable: west			Yes N=19	No N=31	
rain_on_snow_often	binary {0, 1}	Fisher exact	0,11	0,39	0,050
Group variable: northerly_exposed			Yes N=30	No N=20	
snowpack_temp_important	binary {0, 1}	Fisher exact	0,33	0,05	0,033
Group variable: sealevel>2000			Yes N=27	No N=22	
slope_dwarfshrub_no	binary {0, 1}	Fisher exact	0,67	0,27	0,010
heli_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	2,78	2,05	0,012
heli_dsa_often	binary {0, 1}	Fisher exact	0,85	0,45	0,005
control_operations_feb	metric [#]	Mann Whitney U	1,23	2,11	0,036
control_operations_may	binary {0, 1}	Fisher exact	0,31	0,00	0,014
Group variable: sealevel<2000			Yes N=8	No N=41	
slope_dwarfshrub_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,75	0,83	0,015
slope_dwarfshrub_some	binary {0, 1}	Fisher exact	0,63	0,15	0,009
slope_dwarfshrub_no	binary {0, 1}	Fisher exact	0,13	0,56	0,049
#_release_points_dsa	metric [#]	Mann Whitney U	56,88	86,54	0,017
#_release_points_wsa	metric [#]	Mann Whitney U	9,13	34,10	0,009
release_points_dsa/km_ski_slope	metric [%]	Mann Whitney U	0,82	1,14	0,019
Group variable: sealevel>2500			Yes N=6	No N=43	
south	binary {0, 1}	Fisher exact	0,17	0,67	0,027
40°_steeper_no	binary {0, 1}	Fisher exact	0,67	0,23	0,048
weather_rain	ordinal {0, 1, 2, 3}	Fisher exact	1,67	2,74	0,010
weather_rain_very_important	binary {0, 1}	Fisher exact	0,33	0,88	0,007

weather_overcloud_night	ordinal {0, 1, 2, 3}	Fisher exact	1,17	2,58	0,017
weather_overcloud_night_veryimportant	binary {0, 1}	Fisher exact	0,33	0,77	0,048
weather_overcloud_night_no	binary {0, 1}	Fisher exact	0,50	0,07	0,019
weather_wind_no	binary {0, 1}	Fisher exact	0,67	0,16	0,018
snowpack_pen_depth_no	binary {0, 1}	Fisher exact	0,50	0,09	0,031
snowpack_basement	ordinal {0, 1, 2, 3}	Fisher exact	1,17	2,44	0,020
snowpack_basement_very_important	binary {0, 1}	Fisher exact	0,17	0,65	0,035
snowpack_basement_no	binary {0, 1}	Fisher exact	0,50	0,09	0,031
rain_on_snow_no	binary {0, 1}	Fisher exact	0,67	0,16	0,018
info_index_frequency	metric {Σ i(0..3)}	Mann Whitney U	9,33	13,95	0,018
info_class1_index	metric {Σ i(0..3)}	Mann Whitney U	2,83	4,81	0,016
control_operations_feb	metric [#]	Mann Whitney U	0,00	1,85	0,001
control_operations_mar	metric [#]	Mann Whitney U	2,33	4,13	0,043
loose_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,50	1,63	0,026
Group variable: slope_rock_many			Yes N=7	No N=43	
steep_frequency_index	metric {Σ i(0..3)}	Mann Whitney U	6,18	3,93	0,025
35°_40°_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,14	1,81	0,005
35°_40°_many	binary {0, 1}	Fisher exact	0,57	0,09	0,009
35°_40°_some	binary {0, 1}	Fisher exact	0,14	0,67	0,012
small_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,29	1,47	0,046
secondary_slab_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,86	1,16	0,009
secondary_slab_wsa_often	binary {0, 1}	Fisher exact	0,43	0,02	0,007
Group variable: gramineous_slope_many			Yes N=8	No N=42	
35°_40°_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,38	1,76	0,001
35°_40°_many	binary {0, 1}	Fisher exact	0,63	0,07	0,001
35°_40°_some	binary {0, 1}	Fisher exact	0,25	0,67	0,047
medium_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,13	1,19	0,004
medium_aval_frequency	binary {0, 1}	Fisher exact	0,38	0,00	0,003
large_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,75	0,29	0,039
slab_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,00	1,24	0,041
slab_wsa_often	binary {0, 1}	Fisher exact	0,38	0,07	0,044

Table A.2: Test results for chapter '4.3.2 Weather situations and timing of control operation'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: rain_on_snow_often			Yes N=14	No N=36	
control_operations_feb	metric [#]	Mann Whitney U	2,17	1,53	0,048
Group variable: warm_periods_often			Yes N=27	No N=23	
large_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,56	0,13	0,023
large_aval_few	binary {0, 1}	Fisher exact	0,30	0,04	0,028
large_aval_no	binary {0, 1}	Fisher exact	0,59	0,91	0,012
surface_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,59	1,04	0,041
surface_wsa_sometimes	binary {0, 1}	Fisher exact	0,30	0,04	0,028
surface_wsa_no	binary {0, 1}	Fisher exact	0,30	0,61	0,045
ground_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,70	0,57	0,001

ground_wsa_often	binary {0, 1}	Fisher exact	0,33	0,09	0,046
ground_wsa_sometimes	binary {0, 1}	Fisher exact	0,26	0,00	0,011
ground_wsa_no	binary {0, 1}	Fisher exact	0,22	0,61	0,009
aval_activity_index	metric {Σ i(0..3)}	Mann Whitney U	7,30	2,53	0,005
info_index_frequency	metric {Σ i(0..3)}	Mann Whitney U	14,78	11,74	0,010
info_class1_index	metric {Σ i(0..3)}	Mann Whitney U	5,11	3,96	0,042
info_class2_index	metric {Σ i(0..3)}	Mann Whitney U	4,37	3,00	0,005
control_operations_apr	metric [#]	Mann Whitney U	5,35	3,80	0,045
#_control_operations	metric [#]	Mann Whitney U	13,88	9,30	0,017
amount_explosives_wsa	metric [kg]	Mann Whitney U	297,40	131,50	0,002

Table A.3: Test results (part I) for chapter '4.3.3 Release methods and amount of explosives'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: amount_explosives_wsa>0,2T			Yes N=10	No N=36	
info_NXD_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,80	0,67	0,008
Info_NXD_important	binary {0, 1}	Fisher exact	0,40	0,03	0,006
amount_explosives_dsa>=2T	binary {0, 1}	Fisher exact	0,70	0,25	0,020
gazex_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	1,70	0,56	0,023
gazex_dsa_often	binary {0, 1}	Fisher exact	0,50	0,17	0,043
gazex_dsa_no	binary {0, 1}	Fisher exact	0,40	0,81	0,020
gazex_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	1,00	0,47	0,006
gazex_wsa_rarely	binary {0, 1}	Fisher exact	0,30	0,00	0,008
gazex_wsa_no	binary {0, 1}	Fisher exact	0,40	0,81	0,020
tower_wsa_often	binary {0, 1}	Fisher exact	0,20	0,00	0,043
#_release_points_dsa	metric [#]	Mann Whitney U	186,80	64,67	0,010
total_amount_explosives	metric [kg]	Mann Whitney U	4420,00	1295,56	0,001
total_amount_explosives_inkl_gazex	metric [kg]	Mann Whitney U	5068,40	1382,89	0,001
amount_explosives_wsa/total	metric [%]	Mann Whitney U	20,97	10,61	0,003
amount_explosives/release_points_wsa	metric [%]	Mann Whitney U	25,51	5,48	0,000
index_sum_auto_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	2,60	1,25	0,044
Group variable: total_amount_explosives_dsa>2T			Yes N=16	No N=30	
ropeway_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	2,25	1,17	0,009
ropeway_dsa_often	binary {0, 1}	Fisher exact	0,75	0,27	0,004
avalancheur_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,75	0,14	0,007
avalancheur_dsa_rarely	binary {0, 1}	Fisher exact	0,19	0,00	0,037
avalancheur_dsa_no	binary {0, 1}	Fisher exact	0,63	0,93	0,015
rak_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,94	0,30	0,020
rak_dsa_rarely	binary {0, 1}	Fisher exact	0,25	0,03	0,043
rak_dsa_no	binary {0, 1}	Fisher exact	0,50	0,87	0,013
hand_dsa_often	binary {0, 1}	Fisher exact	0,94	0,63	0,035
ski_area_slope_km	metric [km]	Mann Whitney U	90,00	65,24	0,037
#_release_points_dsa	metric [#]	Mann Whitney U	173,31	47,43	0,000
#_release_points_wsa	metric [#]	Mann Whitney U	57,00	17,43	0,026
amount_explosives_wsa	metric [kg]	Mann Whitney U	497,50	97,83	0,004
amount_explosives_wsa/total	metric [%]	Mann Whitney U	9,25	14,79	0,040

amount_explosives/release_points_dsa	metric [%]	Mann Whitney U	73,24	18,83	0,015
index_sum_projectile_devices_dsa	metric {Σ i(0..3)}	Mann Whitney U	1,94	0,57	0,001
index_sum_hand_delivery_dsa	metric {Σ i(0..6)}	Mann Whitney U	5,93	5,13	0,016
index_sum_explosives_dsa	metric {Σ i(0..27)}	Mann Whitney U	12,00	8,40	0,001
Group variable: charge_placement_loose_in			Yes N=10	No N=40	
release_success_wsa	metric [%]	Mann Whitney U	18,00	43,51	0,011
index_sum_projectile_devices_dsa	metric {Σ i(0..3)}	Mann Whitney U	2,30	0,63	0,018
Group variable: charge_placement_loose_on			Yes N=22	No N=28	
release_success_wsa>40%	binary {0, 1}	Fisher exact	0,59	0,21	0,009
#_release_points_dsa	metric [#]	Mann Whitney U	122,09	59,54	0,033
release_success_wsa	metric [%]	Mann Whitney U	48,18	29,20	0,007
#_control_operations	metric [#]	Mann Whitney U	14,72	9,29	0,006
index_sum_auto_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	2,14	1,14	0,030
Group variable: charge_placement_slab_in			Yes N=8	No N=39	
#_control_operations	metric [#]	Mann Whitney U	8,00	12,97	0,041
Group variable: charge_placement_slab_on			Yes N=8	No N=39	
#_release_points_dsa	metric [#]	Mann Whitney U	129,70	58,63	0,020
#_control_operations	metric [#]	Mann Whitney U	14,68	9,93	0,015
index_sum_hand_delivery_wsa	metric {Σ i(0..3)}	Mann Whitney U	4,60	3,57	0,033

Table A.4: Test results (part II) for chapter '4.3.3 Release methods and amount of explosives'

variable name	variable type	test method	group mean value	group mean value	group mean value	group mean value	p-value
Group variable: charge_size			n.a. N=12	smaller N=1	same N=19	bigger N=18	
country	nominal {1, 2, 3}	Kruskal Wallis H	2,00	3,00	2,00	1,39	0,046
charge_placement_loose	nominal {0, 1, 2, 3}	Kruskal Wallis H	0,40	2,00	1,82	2,22	0,043
charge_placement_slab	nominal {0, 1, 2, 3}	Kruskal Wallis H	0,00	1,00	1,82	2,00	0,010
Group variable: charge_placement_loose			n.a. N=8	in N=9	on N=15	above N=18	
release_success_wsa	metric [#]	Kruskal Wallis H	23,33	18,89	42,86	48,89	0,041
gazex_frequency_dsa	ordinal {0, 1, 2, 3}	Kruskal Wallis H	0,00	0,22	0,33	1,67	0,002
minen_frequency_dsa	ordinal {0, 1, 2, 3}	Kruskal Wallis H	0,00	0,56	0,00	0,11	0,003
gazex_frequency_wsa	ordinal {0, 1, 2, 3}	Kruskal Wallis H	0,38	0,22	0,20	1,22	0,014
Group variable: charge_placement_slab			n.a. N=10	in N=10	on N=13	above N=17	
#_release_points_dsa	metric [#]	Kruskal Wallis H	73,10	56,80	44,54	145,5	0,033
hand_frequency_wsa	ordinal {0, 1, 2, 3}	Kruskal Wallis H	1,70	1,20	2,38	2,59	0,004
index_sum_hand_delivery_wsa	metric {Σ i(0..3)}	Kruskal Wallis H	3,10	3,40	4,00	4,82	0,044

Table A.5: Test results for chapter '4.3.4 Type and size of released wet snow avalanches'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: loose_wsa_often&sometimes			Yes N=28	No N=22	
steep_frequency_index	metric {Σ i(0..3)}	Mann Whitney U	4,72	3,64	0,046
secondary_frequency_index	metric {Σ i(0..3)}	Mann Whitney U	2,64	1,73	0,044
Group variable: loose_wsa_often			Yes N=14	No N=36	
sluff_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,43	1,33	0,004
sluff_aval_few	binary {0, 1}	Fisher exact	0,00	0,31	0,022
small_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,86	1,39	0,028
small_aval_many	binary {0, 1}	Fisher exact	0,36	0,08	0,030
small_aval_few	binary {0, 1}	Fisher exact	0,07	0,42	0,021
medium_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,71	1,14	0,043
medium_aval_no	binary {0, 1}	Fisher exact	0,00	0,28	0,045
Group variable: slab_wsa_often			Yes N=6	No N=44	
slope_gramineous_many	binary {0, 1}	Fisher exact	0,50	0,11	0,044
slope_gramineous_few	binary {0, 1}	Fisher exact	0,50	0,11	0,044
slope_dwarfshrub_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,67	0,91	0,029
slope_dwarfshrub_many	binary {0, 1}	Fisher exact	0,50	0,07	0,018
small_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,67	1,50	0,013
small_aval_many	binary {0, 1}	Fisher exact	0,50	0,11	0,044
medium_aval_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,50	1,18	0,000
medium_aval_many	binary {0, 1}	Fisher exact	0,50	0,00	0,001
surface_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,67	1,16	0,032
surface_wsa_no	binary {0, 1}	Fisher exact	0,00	0,50	0,028
ground_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,33	1,02	0,035
ground_wsa_often	binary {0, 1}	Fisher exact	0,67	0,16	0,017
Group variable: medium_avalanche_many&some			Yes N=24	No N=26	
secondary_slab_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,63	0,88	0,002
secondary_slab_wsa_often	binary {0, 1}	Fisher exact	0,17	0,00	0,046
secondary_slab_wsa_no	binary {0, 1}	Fisher exact	0,04	0,42	0,002
steep_frequency_index	metric {Σ i(0..3)}	Mann Whitney U	4,87	3,68	0,003
Group variable: large_aval			Yes N=13	No N=37	
secondary_slab_wsa_often	binary {0, 1}	Fisher exact	0,23	0,03	0,049
warm_periods_often	binary {0, 1}	Fisher exact	0,85	0,43	0,012
steep_frequency_index	metric {Σ i(0..3)}	Mann Whitney U	5,55	3,79	0,002

Table A.6: Test results for chapter '4.3.5 Release success rate and reduction of closure times'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: reduction_closure			Yes N=31	No N=17	
loose_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,94	1,29	0,048
loose_wsa_rarely	binary {0, 1}	Fisher exact	0,13	0,47	0,015
ground_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,42	0,88	0,035
ground_wsa_rarely	binary {0, 1}	Fisher exact	0,13	0,47	0,015
release_success_dsa>80%	binary {0, 1}	Fisher exact	0,23	0,00	0,041
info_test_release_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,39	1,47	0,022
info_test_release_very_important	binary {0, 1}	Fisher exact	0,65	0,24	0,015
snowpack_height	ordinal {0, 1, 2, 3}	Fisher exact	2,55	1,71	0,020
snowpack_height_very_important	binary {0, 1}	Fisher exact	0,65	0,29	0,034
snowpack_height_slightly_important	binary {0, 1}	Fisher exact	0,03	0,24	0,047
release_success_wsa>40%&>99kg	binary {0, 1}	Fisher exact	0,39	0,06	0,017
heli_wsa_often	binary {0, 1}	Fisher exact	0,52	0,18	0,031
heli_wsa_sometimes	binary {0, 1}	Fisher exact	0,13	0,41	0,036
wsa_loose&slab_index	metric {Σ i(0..3)}	Mann Whitney U	3,55	2,35	0,008
release_success_wsa	metric [%]	Mann Whitney U	45,33	25,29	0,010
release_success_dsa	metric [%]	Mann Whitney U	66,45	48,82	0,003
info_class1_index	metric {Σ i(0..3)}	Mann Whitney U	5,06	4,06	0,027
snowpack_index_frequency	metric {Σ i(0..3)}	Mann Whitney U	18,32	15,12	0,046
amount_explosives_wsa/total	metric [%]	Mann Whitney U	15,34	9,57	0,011
Group variable: release_success_rate_wsa>60%			Yes N=12	No N=38	
slab_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,08	1,13	0,013
slab_wsa_often	binary {0, 1}	Fisher exact	0,33	0,05	0,024
ground_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,83	0,97	0,048
ground_wsa_sometimes	binary {0, 1}	Fisher exact	0,33	0,08	0,048
release_success_dsa>60%	binary {0, 1}	Fisher exact	0,75	0,39	0,047
info_NXD_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,83	0,58	0,039
snowpack_structure_important	binary {0, 1}	Fisher exact	0,42	0,11	0,027
charge_size	nominal {0, 1, 2, 3, 4}	Fisher exact	2,58	2,21	0,039
charge_placement_loose	nominal {0, 1, 2, 3}	Fisher exact	2,50	1,66	0,035
release_success_dsa	metric [%]	Mann Whitney U	71,67	56,38	0,048

Table A.7: Test results (part I) for chapter '4.3.6 Differences between countries'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: Austria			Yes N=27	No N=23	
1500_2000	binary {0, 1}	Fisher exact	0,62	0,26	0,021
sealevel>2000	binary {0, 1}	Fisher exact	0,38	0,74	0,021
30°_35°_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,81	1,17	0,042
40°_steeper_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,63	0,70	0,001
surface_wsa_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,11	1,61	0,023
ground_wsa_no	binary {0, 1}	Fisher exact	0,56	0,22	0,021
info_test_release_very_important	binary {0, 1}	Fisher exact	0,63	0,30	0,027
reason_wrong_placement_often	binary {0, 1}	Fisher exact	0,00	0,17	0,038
during_after_wet_snowfall	ordinal {0, 1, 2, 3}	Fisher exact	1,81	1,04	0,011
charge_size	nominal {0, 1, 2, 3, 4}	Fisher exact	2,37	2,22	0,016
rak_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,00	1,04	0,000
minen_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,00	0,30	0,016
groomer_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	1,37	0,65	0,030
blasterbox_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,85	0,09	0,027
rak_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,00	0,43	0,002
mean_sealevel	metric [m]	Mann Whitney U	2135,00	2348,00	0,018
ski_area_slope_km	metric [km]	Mann Whitney U	61,00	83,00	0,037
#_control_operations	metric [#]	Mann Whitney U	13,00	10,00	0,041
index_sum_projectile_devices_dsa	metric {Σ i(0..3)}	Mann Whitney U	0,19	1,87	0,000
index_sum_auto_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	2,15	0,91	0,014
index_sum_projectile_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	0,11	0,83	0,007
Group variable: Swiss			Yes N=20	No N=30	
30°_35°_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,55	0,77	0,010
40°_steeper_frequency	ordinal {0, 1, 2, 3}	Fisher exact	0,70	1,67	0,002
info_test_release_very_important	binary {0, 1}	Fisher exact	0,30	0,60	0,048
reason_wrong_placement_often	binary {0, 1}	Fisher exact	0,20	0,00	0,021
ground_wsa_no	binary {0, 1}	Fisher exact	0,20	0,53	0,022
during_after_wet_snowfall	ordinal {0, 1, 2, 3}	Fisher exact	1,00	1,77	0,023
charge_size	nominal {0, 1, 2, 3, 4}	Fisher exact	1,65	2,03	0,042
rak_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	1,50	0,00	0,000
minen_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,35	0,00	0,007
groomer_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,50	1,33	0,031
rak_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,50	0,00	0,001
mean_sealevel	metric [m]	Mann Whitney U	2325,00	2172,00	0,094
ski_area_slope_km	metric [km]	Mann Whitney U	92,00	58,00	0,001
#_control_operations	metric [#]	Mann Whitney U	10,00	13,00	0,081
total_amount_explosives	metric [kg]	Mann Whitney U	2437,00	1619,00	0,040
total_amount_explosives_inkl_gazex	metric [kg]	Mann Whitney U	2622,00	1847,00	0,047
amount_explosives_wsa/total	metric [%]	Mann Whitney U	8,53	16,19	0,035
amount_explosives/release_points_dsa	metric [kg]	Mann Whitney U	62,00	19,00	0,038
index_sum_projectile_devices_dsa	metric {Σ i(0..3)}	Mann Whitney U	2,15	0,17	0,000
index_sum_auto_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	1,05	1,93	0,117
index_sum_projectile_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	0,95	0,10	0,001

Table A.8: Test results (part II) for chapter '4.3.6 Differences between countries'

variable name	variable type	test method	group mean value	group mean value	group mean value	p-value
Group variable: country			AUT N=27	CH N=20	ST/ITA N=3	
control_operations_apr	metric [#]	Kruskal Wallis H	3,80	5,57	3,67	0,290
index_sum_auto_devices_dsa	metric {Σ i(0..3)}	Kruskal Wallis H	2,00	2,96	0,00	0,048

Table A.9: Test results for chapter '4.3.7 Differences between avalanche control operations for ski areas and highways or roads'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: only_ski_area			Yes N=29	No N=21	
info_snowpack_not_available	binary {0, 1}	Fisher exact	0,00	0,19	0,026
weather_humidity_no	binary {0, 1}	Fisher exact	0,10	0,38	0,036
weather_overcloud_night	ordinal {0, 1, 2, 3}	Fisher exact	2,55	2,19	0,031
snowpack_surface_temp	ordinal {0, 1, 2, 3}	Fisher exact	1,93	1,29	0,038
snowpack_decrease_height	ordinal {0, 1, 2, 3}	Fisher exact	1,76	1,14	0,030
snowpack_basement	ordinal {0, 1, 2, 3}	Fisher exact	2,00	1,76	0,009
rain_on_snow_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,55	1,86	0,017
ropeway_dsa_no	binary {0, 1}	Fisher exact	0,31	0,62	0,044
hand_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	2,69	2,33	0,031
ropeway_wsa_no	binary {0, 1}	Fisher exact	0,38	0,71	0,025
amount_explosives_wsa/total	metric [%]	Mann Whitney U	9,81	17,61	0,049

Table A.10: Test results for chapter '4.3.8 Matter of size'

variable name	variable type	test method	group mean value	group mean value	p-value
Group variable: release_points_dsa>100			>100 N=11	<100 N=39	
info_NXD_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,36	0,44	0,034
info_snowpack_frequency	ordinal {0, 1, 2, 3}	Fisher exact	2,64	2,49	0,029
reason_wrong_day_frequency	ordinal {0, 1, 2, 3}	Fisher exact	1,73	0,74	0,007
timing_after_after_last_sundown	binary {0, 1}	Fisher exact	0,82	0,38	0,016
charge_size_bigger	binary {0, 1}	Fisher exact	0,73	0,36	0,042
gazex_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	1,45	0,54	0,010

ropeway_dsa_often	binary {0, 1}	Fisher exact	0,73	0,33	0,036
tower_dsa_often	binary {0, 1}	Fisher exact	0,46	0,15	0,014
avalancheur_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,73	0,23	0,002
minen_frequency_dsa	ordinal {0, 1, 2, 3}	Fisher exact	0,55	0,03	0,006
gazex_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	1,00	0,49	0,035
gazex_frequency_wsa	binary {0, 1}	Fisher exact	0,36	0,08	0,034
avalancheur_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,36	0,13	0,041
rak_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,64	0,08	0,034
minen_frequency_wsa	ordinal {0, 1, 2, 3}	Fisher exact	0,27	0,00	0,008
ski_area_slope_km	metric [km]	Mann Whitney U	108,00	60,80	0,007
#_release_points_wsa	metric [#]	Mann Whitney U	78,55	16,85	0,001
release_points_dsa/km_ski_slope	metric [%]	Mann Whitney U	2,22	0,89	0,047
release_points_wsa/release_points_dsa	metric [%]	Mann Whitney U	0,27	0,48	0,037
#_control_operations	metric [#]	Mann Whitney U	15,27	10,83	0,047
total_amount_explosives	metric [kg]	Mann Whitney U	4250,00	1259,71	0,000
amount_explosives_wsa	metric [kg]	Mann Whitney U	569,44	137,56	0,005
total_amount_explosives_inkl_gazex	metric [kg]	Mann Whitney U	4923,45	1323,14	0,000
index_sum_projectile_devices_dsa	metric {Σ i(0..3)}	Mann Whitney U	2,18	0,62	0,001
index_sum_hand_delivery_dsa	metric {Σ i(0..9)}	Mann Whitney U	6,18	5,03	0,017
index_sum_explosives_dsa	metric {Σ i(0..27)}	Mann Whitney U	12,64	8,51	0,002
index_sum_mechanical_dsa	metric {Σ i(0..3)}	Mann Whitney U	3,18	2,05	0,030
index_sum_projectile_devices_wsa	metric {Σ i(0..3)}	Mann Whitney U	1,27	0,21	0,002
index_sum_explosives_wsa	metric {Σ i(0..27)}	Mann Whitney U	8,45	5,87	0,022
Group variable: release_points_wsa>30			>30 N=14	<30 N=36	
east	binary {0, 1}	Fisher exact	0,86	0,36	0,004
south_east	binary {0, 1}	Fisher exact	0,86	0,47	0,024
south	binary {0, 1}	Fisher exact	0,86	0,53	0,050
southerly_exp	binary {0, 1}	Fisher exact	1,00	0,69	0,022
snowpack_decr_height_very_important	binary {0, 1}	Fisher exact	0,00	0,28	0,045
snowpack_structure	ordinal {0, 1, 2, 3}	Fisher exact	2,00	2,72	0,027
heli_wsa_often	binary {0, 1}	Fisher exact	0,64	0,28	0,025
#_release_points_dsa	metric [#]	Mann Whitney U	168,00	55,58	0,001
release_points_wsa/km_ski_slope	metric [%]	Mann Whitney U	84,61	24,46	0,004
release_points_wsa/release_points_dsa	metric [%]	Mann Whitney U	53,32	39,61	0,019
aval_activity_index	metric {Σ i(0..3)}	Mann Whitney U	7,56	4,15	0,024
snowpack_index_frequency	metric {Σ i(0..3)}	Mann Whitney U	14,00	17,78	0,039
amount_explosives_wsa	metric [kg]	Mann Whitney U	418,75	154,10	0,041
amount_explosives_wsa_inkl_gazex	metric [kg]	Mann Whitney U	436,42	159,44	0,020
amount_explosives/release_points_dsa	metric [%]	Mann Whitney U	15,31	45,68	0,013
index_sum_hand_delivery_wsa	metric {Σ i(0..6)}	Mann Whitney U	4,93	3,61	0,006

Figure A.1: Survey questionnaire (German language)

Fragebogen zur Künstlichen Auslösung von Nassschneelawinen

Herzlichen Dank für Ihre Mitarbeit, Rückgabe bis 1. Mai 2008

Im folgenden Fragebogen werden unter Nassschneelawinen all jene Lawinen verstanden, bei denen der Schnee im Anrissgebiet zumindest teilweise feucht oder nass ist. Wenn der Schnee im Anrissgebiet trocken ist, wird die Lawine als Trockenschneelawine klassifiziert, auch wenn die Lawine in der Sturzbahn feuchten oder nassen Schnee mitnimmt.

1 Allgemeines

1.1 Lawinendienst/Organisation: ______________________

1.2 Name: ______________ Adresse: ______________

email: ______________ Telefon: ______________

1.3 Lawinensicherung für: O Bergbahnen O Gemeindelawinendienst O Tiefbauamt

2 Charakterisierung Gelände

2.1 Wo befinden sich die Anrissgebiete, in denen Nassschneelawinensprengungen durchgeführt werden?

a. Exposition O N O NE O E O SE O S O SW O W O NW

b. Höhenlage in m O 1000-1500 O 1500-2000 O 2000-2500 O über 2500

2.2 Wie steil sind die Anrissgebiete, in denen Nassschneelawinen gesprengt werden?

	einzelne Anrissgeb.	*mehrere Anrissgeb.*	*viele Anrissgeb.*	*keine Anrissgeb.*
a. Steilheit 30°-35°	O	O	O	O
b. Steilheit 35°-40°	O	O	O	O
c. Steilheit über 40°	O	O	O	O

2.3 Wie ist der Untergrund in den Anrissgebieten?

	einzelne Anrissgeb.	*mehrere Anrissgeb.*	*viele Anrissgeb.*	*keine Anrissgeb.*
a. Gras	O	O	O	O
b. Zwergsträucher	O	O	O	O
c. Geröll	O	O	O	O
d. Felsiges Gelände	O	O	O	O

2.4 Wieviel Sprengpunkte gibt es zur Sprengung von *Trocken*schneelawinen im Gebiet? ________

2.5 Wieviel Sprengpunkte gibt es zur Sprengung von *Nass*schneelawinen im Gebiet? ________

2.6 Wie gross sind die gesprengten Nassschneelawinen?

	einzelne	*mehrere*	*viele*	*keine*
a. Rutsche	O	O	O	O
b. kleine Lawinen (bis 100m)	O	O	O	O
c. mittlere Lawinen (bis 1000m)	O	O	O	O
d. grosse Lawinen (über 1000m)	O	O	O	O

2.7 Besonderheiten im Gebiet / Bemerkungen:

3 Schneedecke und Wetter

3.1 Wie wichtig sind folgende Informationen zur Beurteilung der Nassschnee-Lawinensituation?

	unwichtig	*mässig wichtig*	*wichtig*	*nicht vorhanden*
a. Autom. Wetterstationen	O	O	O	O
b. Messfeld	O	O	O	O
c. NXD-Programm	O	O	O	O
d. Schneedeckenuntersuchung	O	O	O	O
e. Testsprengungen	O	O	O	O
f. Lawinenbulletin	O	O	O	O
g. spontane Lawinen	O	O	O	O
h. Andere: __________	O	O	O	

3.2 Wie wichtig sind für Sie folgende Wetterparameter für die Beurteilung ob an diesem Tag Nassschneelawinen gesprengt werden können oder nicht?

	unwichtig	*mässig wichtig*	*wichtig*	*keine Erfahrung*
a. maximale Tagestemperatur	O	O	O	O
b. minimale Tagestemperatur	O	O	O	O
c. Temperaturdifferenz Vortage	O	O	O	O
d. Luftfeuchtigkeit	O	O	O	O
e. Regen	O	O	O	O
f. Neuschnee	O	O	O	O
g. Bewölkungsgrad Nacht	O	O	O	O
h. Bewölkungsgrad Tag	O	O	O	O
i. Sonneneinstrahlung	O	O	O	O
j. Windgeschwindigkeit	O	O	O	O
k. Andere: __________	O	O	O	

3.3 Verwenden Sie für die wichtigen Wetterparameter einfache Regeln für die Beurteilung ob an diesem Tag Nassschneelawinen gesprengt werden können?
(z. B. "Wenn Temperatur auf 2000m über 5°C, dann Sprengungen möglich.")

a. O Nein.

b. O Ja, ich verwende folgende Regeln:

3.4 Wie wichtig sind für Sie folgende Schneedeckenparamter für die Beurteilung ob an diesem Tag Nassschneelawinen gesprengt werden können oder nicht?

		unwichtig	mässig wichtig	wichtig	keine Erfahrung
a.	Krustendicke am Morgen	O	O	O	O
b.	Schneeoberflächentemp.	O	O	O	O
c.	Einsinktiefe	O	O	O	O
d.	Schneehöhenabnahme	O	O	O	O
e.	Schneehöhe	O	O	O	O
f.	Schneedeckenfundament	O	O	O	O
g.	Schneedeckenaufbau	O	O	O	O
h.	Schneetemperatur	O	O	O	O
i.	Andere:_______________	O	O	O	

3.5 Verwenden Sie für die wichtigen Schneedeckenparameter einfache Regeln für die Beurteilung ob an diesem Tag Nassschneelawinen gesprengt werden können?
(z. B. "Wenn Schneeoberflächentemperatur mehr als 6 Stunden 0°, dann Sprengungen möglich.")

a. O Nein.
b. O Ja, ich verwende folgende Regeln:

3.6 Wie oft werden bei folgenden Wettersituationen Nassschneelawinen gesprengt?

		selten	manchmal	oft	nie
a.	während / nach intensivem Regen	O	O	O	O
b.	während / nach feuchtem Schneefall	O	O	O	O
c.	während / nach langen Wärmeperioden	O	O	O	O
d.	bei schneller Erwärmung nach Neuschnee	O	O	O	O
e.	Andere: _______________	O	O	O	

3.7 Wie oft werden im Durchschnitt in folgenden Monaten Nassschneelawinensprengungen durchgeführt?
Bitte geben Sie die Anzahl der Spreng-Kampagnen an:

		nie	1-2mal	3-5mal	5-7mal	öfter
a.	November	O	O	O	O	O
b.	Dezember	O	O	O	O	O
c.	Januar	O	O	O	O	O
d.	Februar	O	O	O	O	O
e.	März	O	O	O	O	O
f.	April	O	O	O	O	O
g.	Mai	O	O	O	O	O
h.	Juni	O	O	O	O	O

3.8 Sonstige Erfahrungen / Bemerkungen:

4 Sprengzeitpunkt

4.1 Welches ist der optimale Sprengzeitpunkt für Nassschneelawinen, wenn Sprengungen während oder nach langer Wärmeperiode durchgeführt werden?

a. O Sofort nachdem die Kruste geschmolzen ist.
b. O Nach mehrstündiger Sonneneinstrahlung.
c. O Kurz nach den letzten Sonnenstrahlen.
d. O Anderer / eigene Beobachtungen:

4.2 Welches ist der optimale Sprengzeitpunkt für Nassschneelawinen, wenn Sprengungen während oder nach intensivem Regen durchgeführt werden?

a. O Kurz nach Beginn des Regens.
b. O Nach mehrstündigem Regen.
c. O Nach dem Regen.
d. O Anderer / eigene Beobachtungen:

4.3 Sonstige Erfahrungen / Bemerkungen:

5 Durchführung der Sprengung

5.1 Können die Auslaufgebiete der Nassschneelawinen zu jeder Tageszeit kurzfristig gesperrt werden, um Testsprengungen durchzuführen?

a. O Ja.
b. O Nein, Grund: O Skibetrieb O Andere:_______________

5.2 Welche Methoden werden zur Künstlichen Auslösung von **Trockenschneelawinen** verwendet?

		selten	manchmal	oft	nicht vorhanden
a.	Gasex	O	O	O	O
b.	Sprengseilbahn	O	O	O	O
c.	Sprengmast	O	O	O	O
d.	Lawinenorgel	O	O	O	O
e.	Avalancheur	O	O	O	O
f.	Helikopter	O	O	O	O
g.	Rakrohr	O	O	O	O
h.	Gratausleger	O	O	O	O
i.	Handsprengung	O	O	O	O
j.	Minenwerfer	O	O	O	O
k.	Pistenmaschine	O	O	O	O
l.	Abtreten mit Ski	O	O	O	O
m.	Andere:_______________	O	O	O	

5.3 Welche Methoden werden zur Künstlichen Auslösung von **Nassschneelawinen** verwendet?

		selten	*manchmal*	*oft*	*nicht vorhanden*
a.	Gasex	O	O	O	O
b.	Sprengseilbahn	O	O	O	O
c.	Sprengmast	O	O	O	O
d.	Lawinenorgel	O	O	O	O
e.	Avalancheur	O	O	O	O
f.	Helikopter	O	O	O	O
g.	Rakrohr	O	O	O	O
h.	Gratausleger	O	O	O	O
i.	Handsprengung	O	O	O	O
j.	Minenwerfer	O	O	O	O
k.	Pistenmaschine	O	O	O	O
l.	Abtreten mit Ski	O	O	O	O
m.	Andere:_______________	O	O	O	

5.4 Eignen sich für die Künstliche Auslösung von Nassschneelaw. bestimmte Methoden besonders gut?

a. O Nein, es ist egal welche Methode man anwendet.

b. O Ja, folgende Methoden:_______________

Grund:

5.5 Werden zum Sprengen von Nassschneelawinen andere Ladungsgrössen verwendet als bei Trockenschneelawinen?

	kleiner	*gleich gross*	*grösser*
Ladungsgrösse	O	O	O

5.6 Wie wird bei Nassschneelawinen der beste Sprengerfolg erzielt?

		Sprengung im Schnee	*Oberflächensprengung*	*Überschneesprengung*
a.	nasse Lockerschneelawinen	O	O	O
b.	nasse Schneebrettlawinen	O	O	O

5.7 Wie hoch war der durchschnittliche Sprengstoffverbrauch/Munitionsverbrauch in den letzten Wintern?

		Insgesamt	davon für Nassschneelawinensprengungen
a.	Sprengstoff	_______kg	_______kg
b.	MW-Granaten	_______Stk	_______Stk
c.	Rak-Rohr-Granaten	_______Stk	_______Stk
d.	Gasex	____Schuss	____Schuss

5.8 Ist der Sprengstoffverbrauch/Munitionsverbrauch für Nassschneelawinen - über die letzten Jahre betrachtet - angestiegen?

a. O Nein.

b. O Ja, Grund:_______________

5.9 Sonstige Erfahrungen / Bemerkungen:

6 Sprengerfolg

6.1 Wie hoch ist der Sprengerfolg?

	positive Sprengungen in %	*unter 20%*	*20%-40%*	*40%-60%*	*60-80%*	*über 80%*
a.	Nassschneelawinen	O	O	O	O	O
b.	Trockenschneelawinen	O	O	O	O	O

6.2 Hat sich der Sprengerfolg bei Nassschneelawinen in den letzten Jahren verändert?

a. O Nein.

b. O Ja, er ist gesunken, Grund:

c. O Ja, er ist gestiegen, Grund:

6.3 Welcher Lawinentyp wird hauptsächlich gesprengt?

		einzelne	*mehrere*	*viele*	*keine*
a.	nasse Schneebrettlawinen	O	O	O	O
b.	nasse Lockerschneelawinen	O	O	O	O
c.	Oberlawinen	O	O	O	O
d.	Bodenlawinen	O	O	O	O

6.4 Wurden sekundäre Auslösungen durch ausgelöste Nassschneelawinen beobachtet?

		selten	*manchmal*	*oft*	*nie*
a.	nasse Lockerschneelawinen	O	O	O	O
b.	nasse Schneebrettlawinen	O	O	O	O

6.5 Wurden Fernauslösungen beim Sprengen von Nassschneelawinen beobachtet?

		selten	*manchmal*	*oft*	*nie*
a.	nasse Lockerschneelawinen	O	O	O	O
b.	nasse Schneebrettlawinen	O	O	O	O

6.6 Welches sind die Ursachen für einen negativen Sprengerfolg?

		selten	*manchmal*	*oft*	*nie*
a.	falscher Tag	O	O	O	O
b.	falscher Zeitpunkt - zu früh	O	O	O	O
c.	falscher Zeitpunkt - zu spät	O	O	O	O
d.	schlechte Ladungsplatzierung	O	O	O	O

6.7 Können die Sperrzeiten durch die Künstliche Lawinenauslösung von Nassschneelawinen wesentlich reduziert werden?

a. O Nein.

b. O Ja.

7 Besondere Beobachtungen und Erfahrungen beim Sprengen von Nassschneelawinen

Weitere Bemerkungen können auch auf der Rückseite angeführt werden!

Appendix B: Expert interviews

Figure B.1: Guideline for expert interviews (German language)

LEITFADEN EXPERTENINTERVIEW

Datum: Ort:

1. Begrüssung und Einleitung

1.1 Vorstellung Fragestellung, Ablauf des Interviews.
1.2 Anonymität, Authorisierung, Veröffentlichung, Tonband.
1.3 Fragen zur Person: Tätigkeit? Wie lange schon?

2. Definition und Klassifikation von Nassschneelawinen

2.1 Wie definieren Sie Nassschneelawinen?
2.2 Definition nach internationaler Lawinenklassifikation.
2.3 Klassifizierung von Nassschneelawinen anhand von 5 Beispielen (Bilder).
2.4 Häufigkeit von unterschiedlichen Lawinentypen im Gebiet?
2.5 Einfluss von Schneedecke, Gelände, Exposition, Höhenlage, Untergrund auf Lawinentyp?

3. Bestimmung vom optimalen Sperngzeitpunkt

A.) Niederschlagsfreie Wetterphase mit milden Temperaturen und hoher Strahlung.
B.) Regensituation.
C.) Schnelle und starke Erwärmung mit vorherigem Schneefall.

3.1 Wie häufig kommt eine solche Situation in Ihrem Gebiet vor?
3.2 Welche Schnee- und Wetterdaten werden für die Beurteilung herangezogen?
3.3 Welchen Einfluss hat der Schneedeckenaufbau (unterschiedliche Szenarien)?
Schneetemperatur?
Schneefeuchtigkeit?
Schneedeckenaufbau?
3.4 Reagieren Schneedecken mit Schwachschichten oder Neuschnee früher auf Durchfeuchtung?
3.5 Einfluss von Eislamellen und kapillaren Barrieren?
3.6 Welches sind die auslösenden Faktoren (Zusatzbelastung, Festigkeitsverlust, ...)?
3.7 Wann ist ein Sprengeinsatz absehbar?
3.8 Welches ist der optimale Sprengzeitpunkt?
3.9 Negative Sprengungen - Ursachen und Rückschlüsse?

4. Ladungsplatzierung, Ladungsgrössen und Sprengmethoden

4.1 Welche Ladungsplatzierung eignet sich für die Auslösung von nassen SBL bzw. nassen LSL?
4.2 Welche Ladungsposition eignet sich für die Auslösung von nassen SBL bzw. nassen LSL?
4.3 Welche Ladungsgröße eignet sich für die Auslösung von nassen SBL bzw. nassen LSL?
4.4 Wirkungszone in Abhängigkeit von Ladungsposition und Ladungsgrösse?
4.5 Erfahrungen mit verschiedenen Sprengmethoden?

5. Sprengerfolg

5.1 Welchen Einfluss haben die Sprengergebnisse von Trockenschneelawinen auf die NSL-Aktivität?
5.2 Wann wird eine Sprengung als positiv klassiert?
5.3 Wie beurteilen Sie den Anstieg der Auslösewahrscheinlichkeit im Tagesverlauf?
5.4 Wie beurteilen Sie den Rückgang der Auslösewahrscheinlichkeit am Abend?
5.5 Beobachtung von Sekundär- oder Fernauslösungen?
5.6 Nutzen und Schadenspotential?

Table B.1: Number of codings per interview and category

Hypothesis A: The necessary amount of liquid water to provoke wet snow instabilities depends on the snowpack structure.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category A.1.		1	1		3	1			1				1	1	9
Category A.2.		1		1	1	1		1	1	1					7
Category A.3.		1	1	1	2	2	1	1	1	1			1	1	13
Category A.4.			2		1	2		1	2	1			1		10

Hypothesis B: Prediction of wet snow instabilities with regard to the necessary amount of liquid water is difficult during warm weather periods. Instabilities through rain on snow events are more predictable.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category B.1.		1		2	1	1		2	1		1	1	1	1	12
Category B.2.	1	3	5	1	2	2	1	3	1	2	1	2	3	1	28
Category B.3.	1		1	5	4		1	7	1	1	2		1	2	26
Category B.4.	1	1	1	1	1	1			1				1	1	9
Category B.5.				1	1	1			1				1		5
Category B.6.				2									1		3
Category B.7.			1					2	1	1					5

Hypothesis C: During warm weather periods with high radiation, the chance of release for wet snow avalanches increases abruptly or exponentially with increased time and intensity of solar radiation.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category C.1.			1	2	1	1		1		1	1		1		9

Hypothesis D: In fully-wet snowpack conditions timing of the control operations just after the last sundown increases fracture propagation potential - however, the window of success is very short.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category D.1.		1	2		1	1	1	1	1	1	1	1	1	1	13
Category D.2.		1	1	1	1				1		1				6

Hypothesis E: Different types of wet snow avalanches exist. Wet loose snow avalanches are most frequently released. Slab avalanches are less frequently triggered and they do have different morphologies. The expected avalanche type depends on snowpack properties.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category E.1.		1	1	1		1	1		1	1	1		1	1	10
Category E.2.		1	1	1	1	1	1	1	1	1	1	1	1	1	13
Category E.3.		1	1		1	1		1	1	1	1	1	1	1	11
Category E.4.		1	2	2		3		1	1	2		3	2	1	18
Category E.5.	1				2					1			1		5
Category E.6.		1	4	1	4	4		10	3	3		1	4		35

Hypothesis F: The effective range in wet snow conditions is limited to the area around the crater zone. For charges fired on or above the snowpack, the effective range is slightly higher but still considerably lower than in dry snow conditions.

	Interview 1.	Interview 2	Interview 3	Interview 4	Interview 5	Interview 6	Interview 7	Interview 8	Interview 9	Interview 10	Interview 11	Interview 12	Interview 13	Interview 14	Total
Category F.1.		3	1	1	2	1		1	1				1	1	12
Category F.2.	1	1	1	1	2			1	1	2			1	1	12

Hypothesis G: To release wet loose snow avalanches, charge placement within the starting zone is crucial for release success. Charge size and charge position relative to the snow surface are secondary.

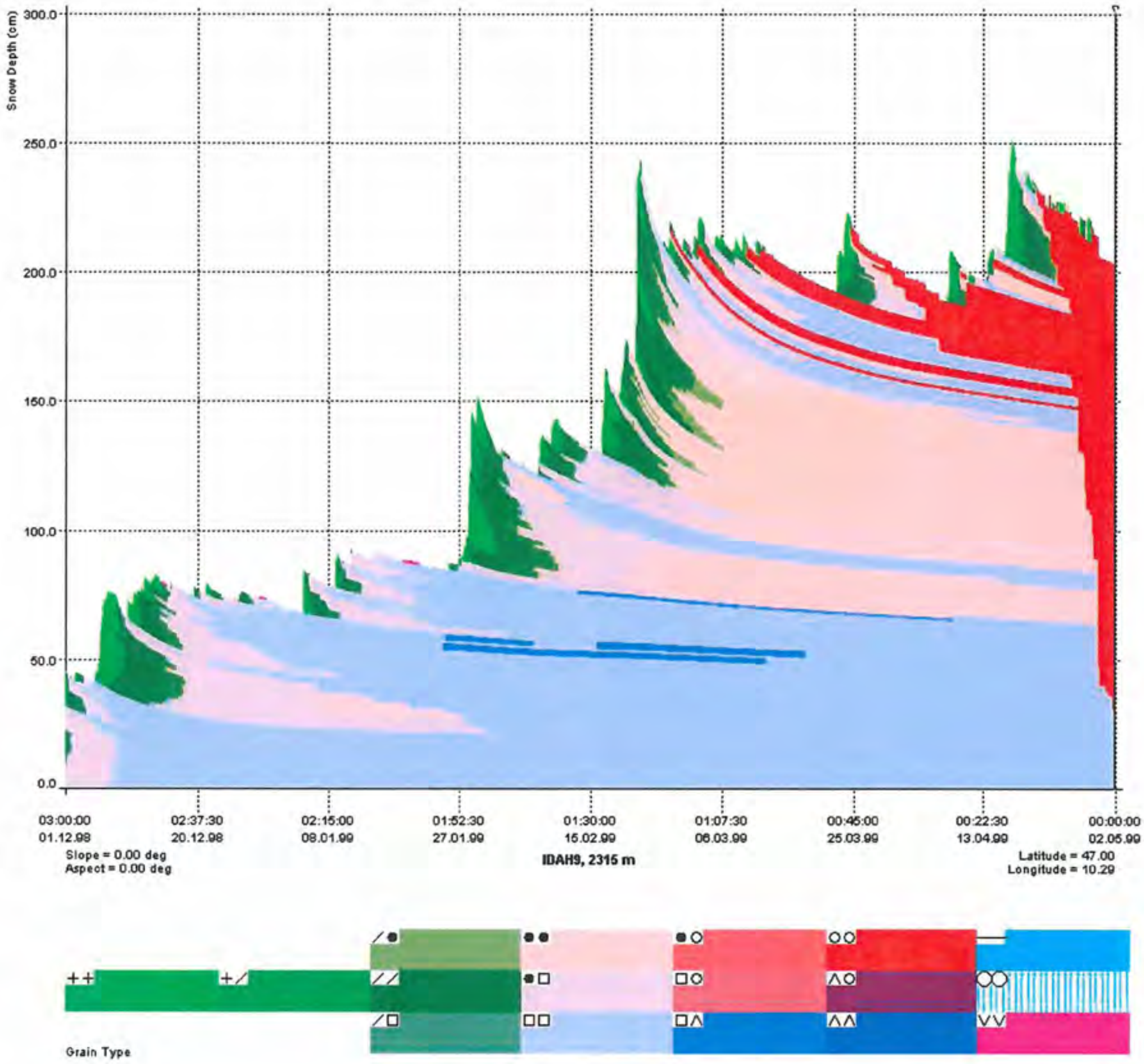
Category G.1.	1	1	3	2	2	3		2	2	5	1	4	2	1	29
Category G.2.			1	1	1	1	1			1			1	1	8
Category G.3.		1	1	1	1	2		1	1	1	1	1	2		13
Category G.4.	1	3	2	1	1	2		1	4		1	4	4	1	25
Category G.5.			3	1	1	1	1	1	2	3	1	2	2	2	20

Hypothesis H: Charge placement on or above the snowpack and bigger charge sizes are preferable to release wet slab avalanches.

Category H.1.		1	1					1		1		1			5
Category H.2.			1		2	2			1			2	1		9
Category H.3.					1	1		1		1			1		5
Category H.4.	1					1		4					1		7

Appendix C: Case study

Figure C.1: SNOWPACK simulation (grain type), winter 1998/99



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

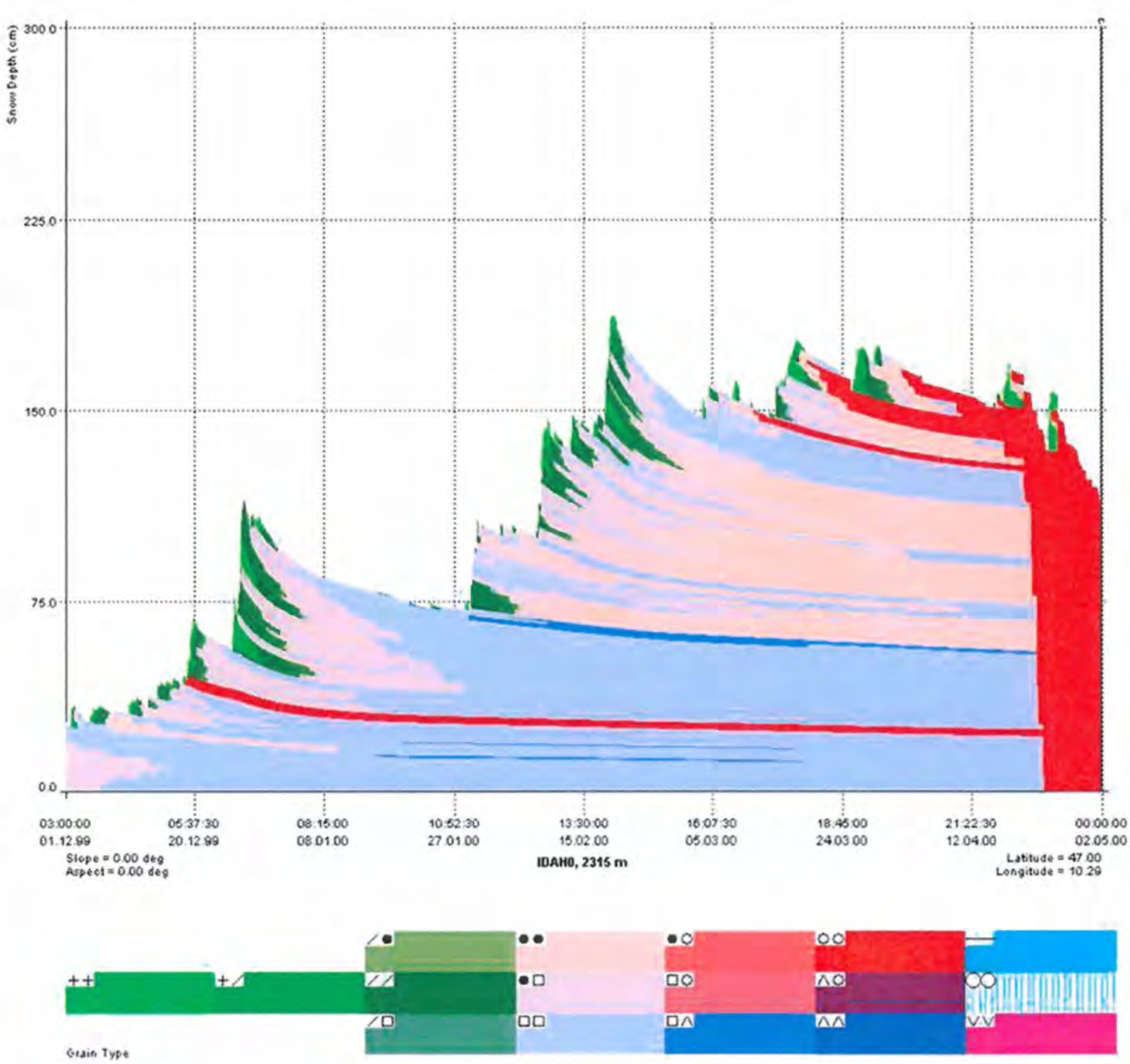
Simulation period: 27.11.1998 - 01.05.1999

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.2: SNOWPACK simulation (grain type), winter 1999/00



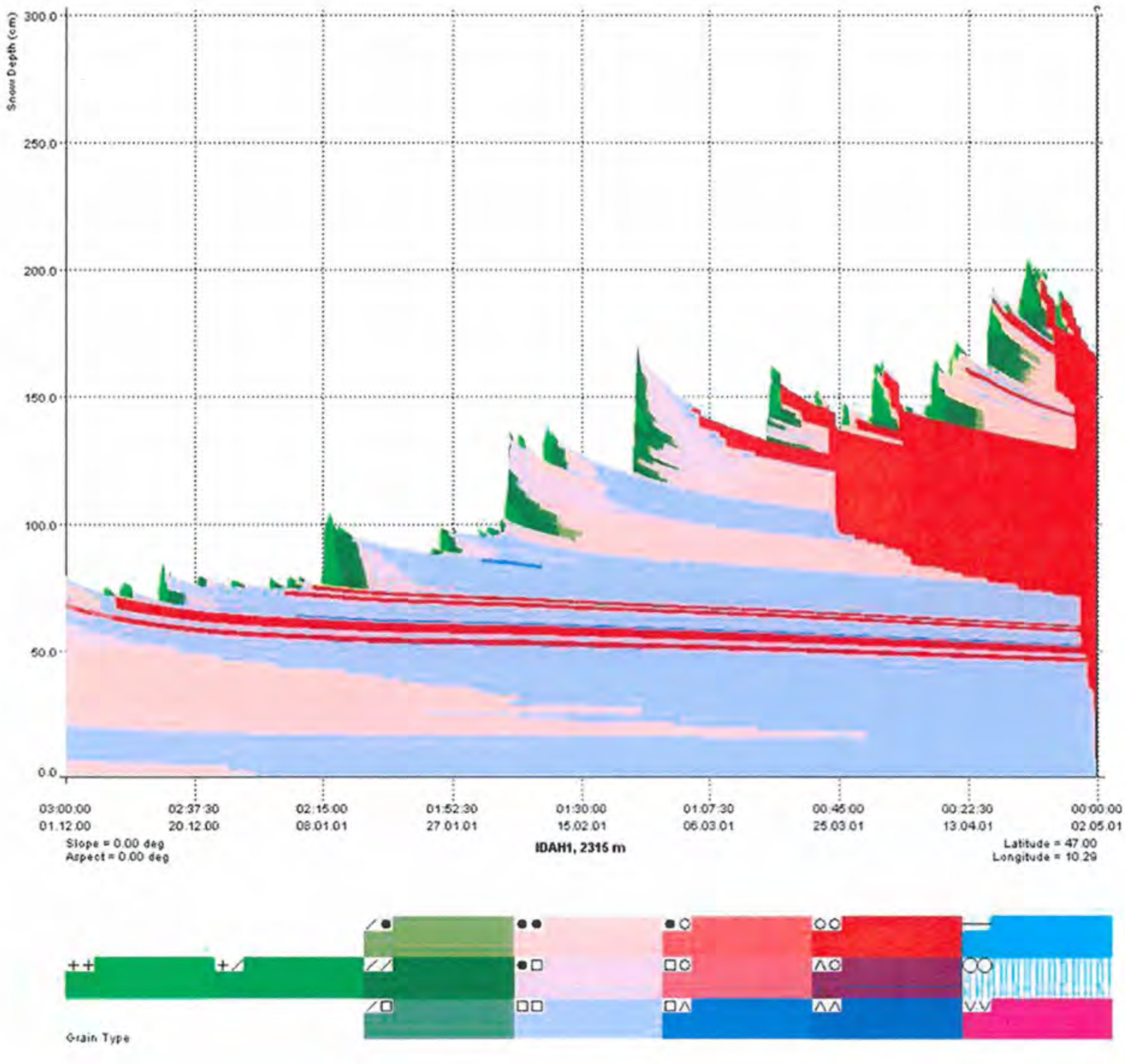
Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

Simulation period: 22.11.1999 - 01.05.2000

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.
Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.
Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.3: SNOWPACK simulation (grain type), winter 2000/01



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

Simulation period: 03.11.2000 - 01.05.2001

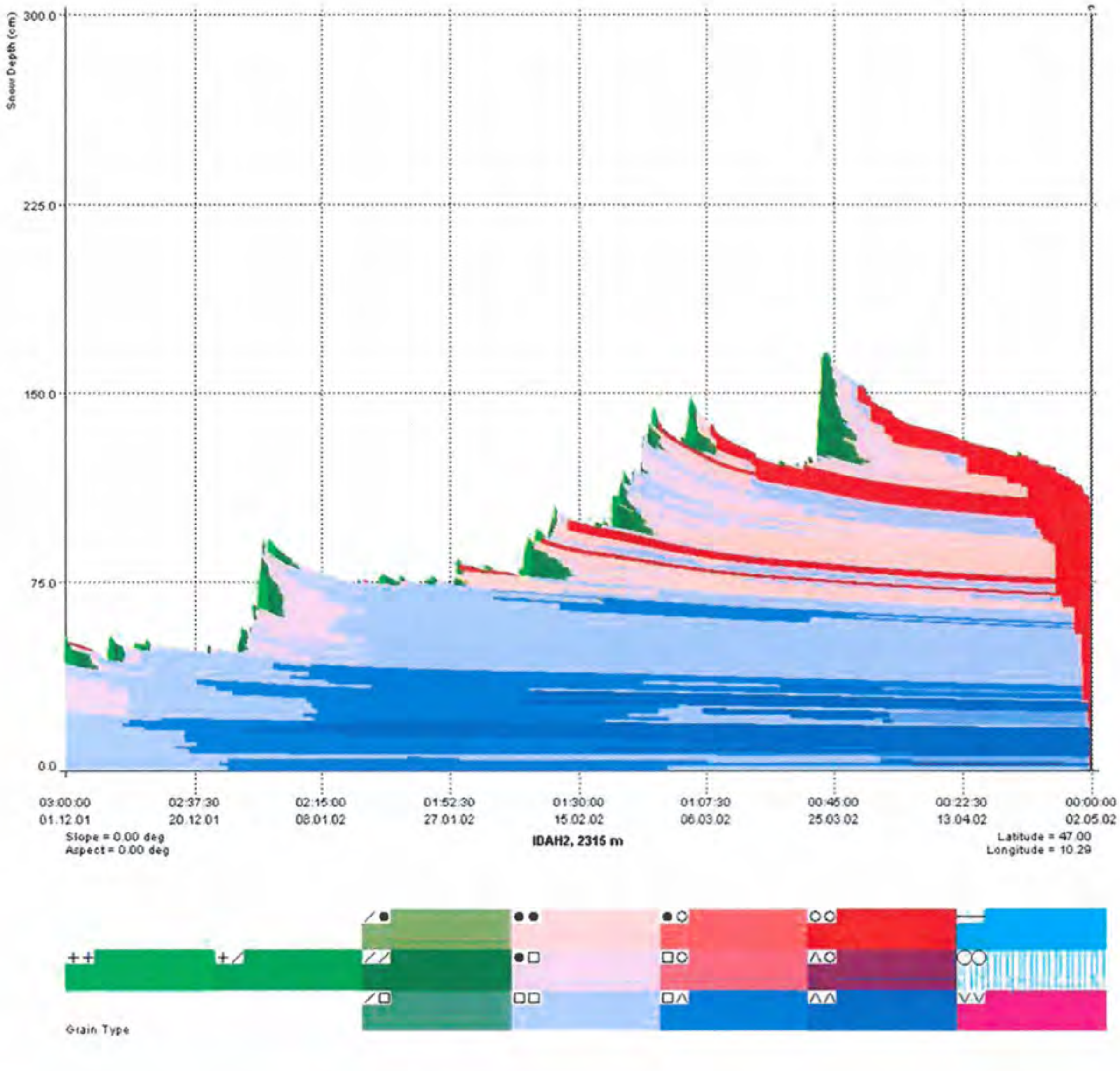
Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C.

Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.4: SNOWPACK simulation (grain type), winter 2001/02



Input data was composed of data from the following weather stations:

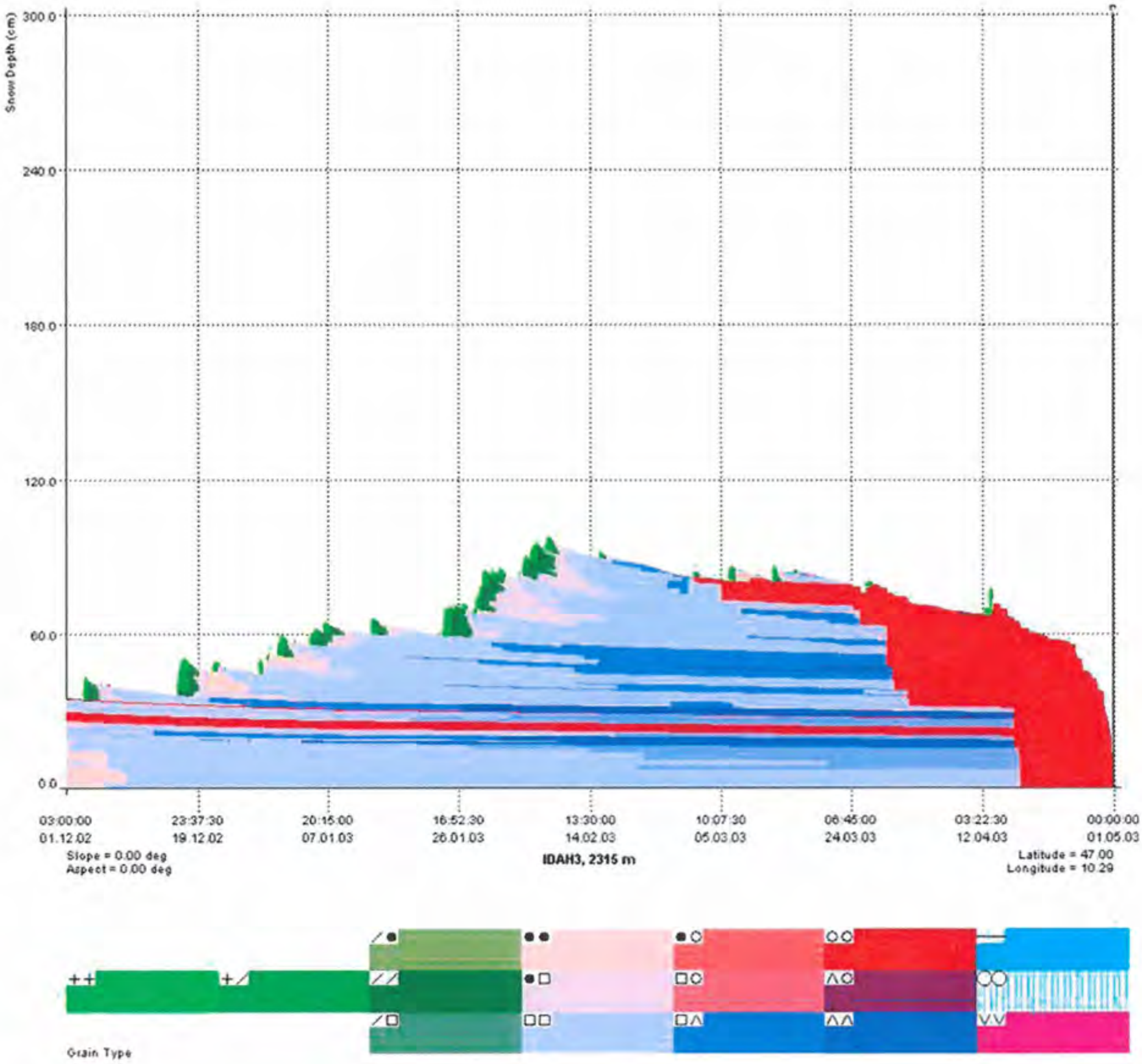
Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

Simulation period: 07.11.2001 - 01.05.2002

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions. Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.5: SNOWPACK simulation (grain type), winter 2002/03



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

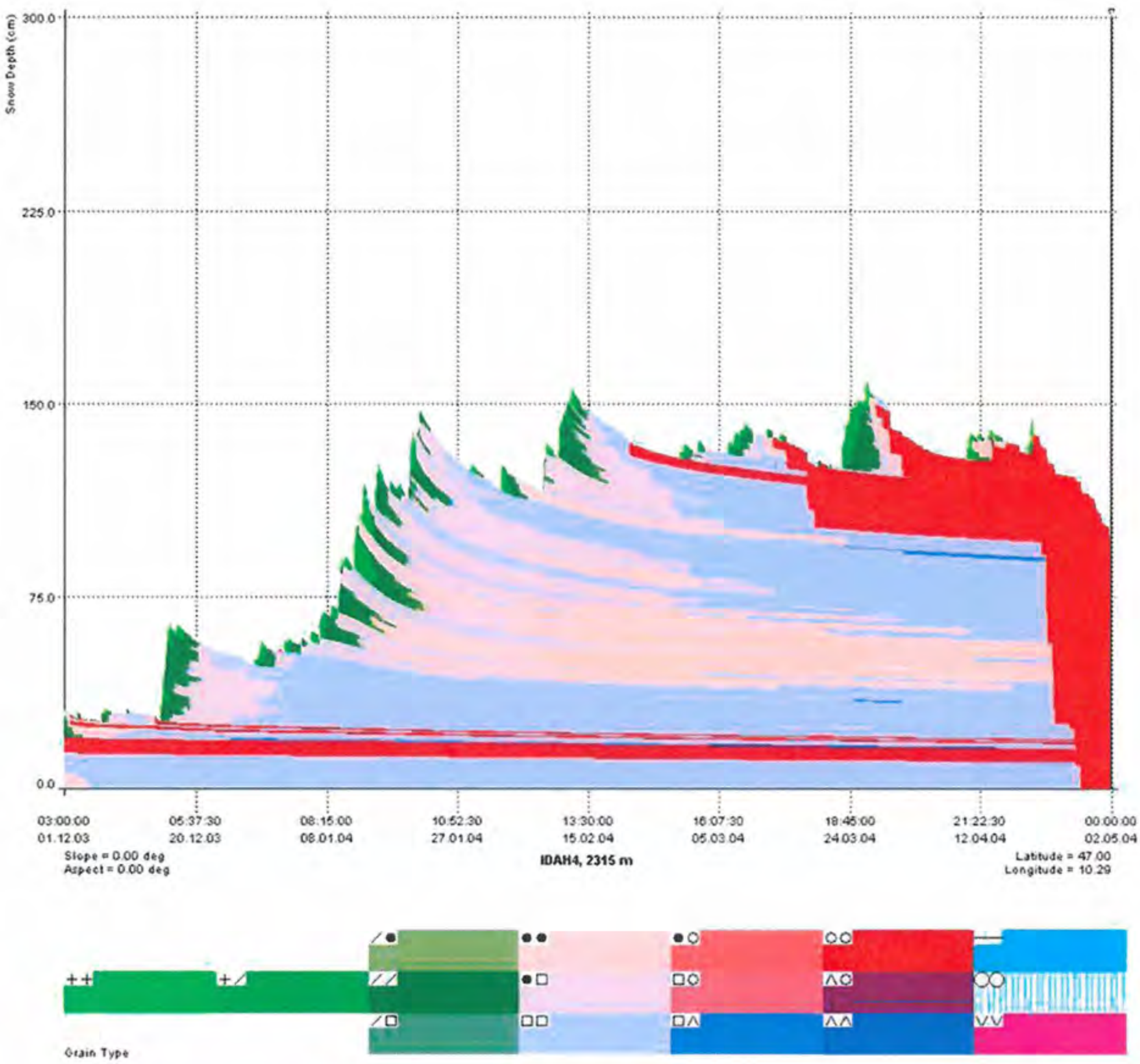
Simulation period: 01.11.2002 - 30.04.2003

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.6: SNOWPACK simulation (grain type), winter 2003/04



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

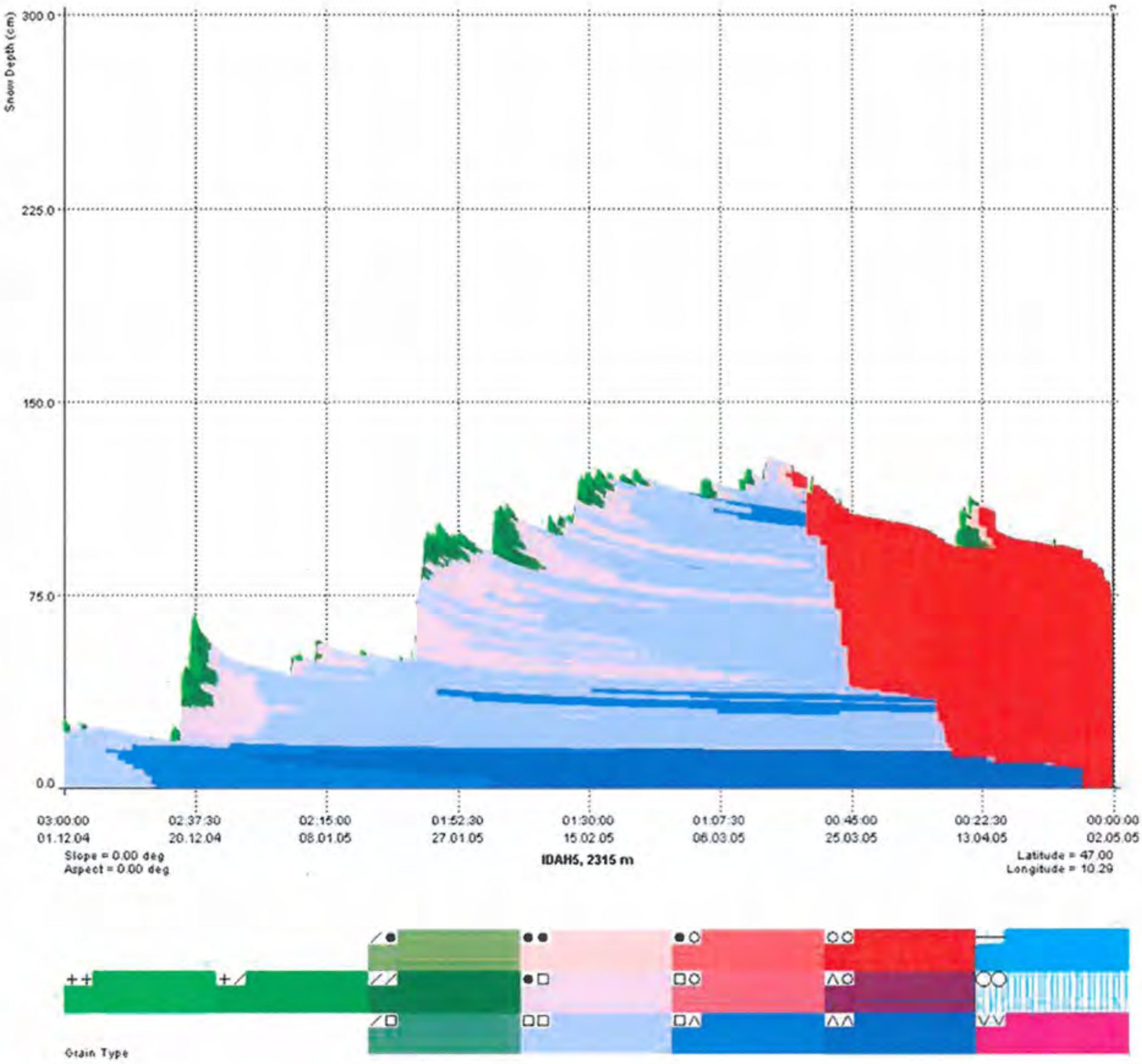
Simulation period: 01.11.2003 - 01.05.2004

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.7: SNOWPACK simulation (grain type), winter 2004/05



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

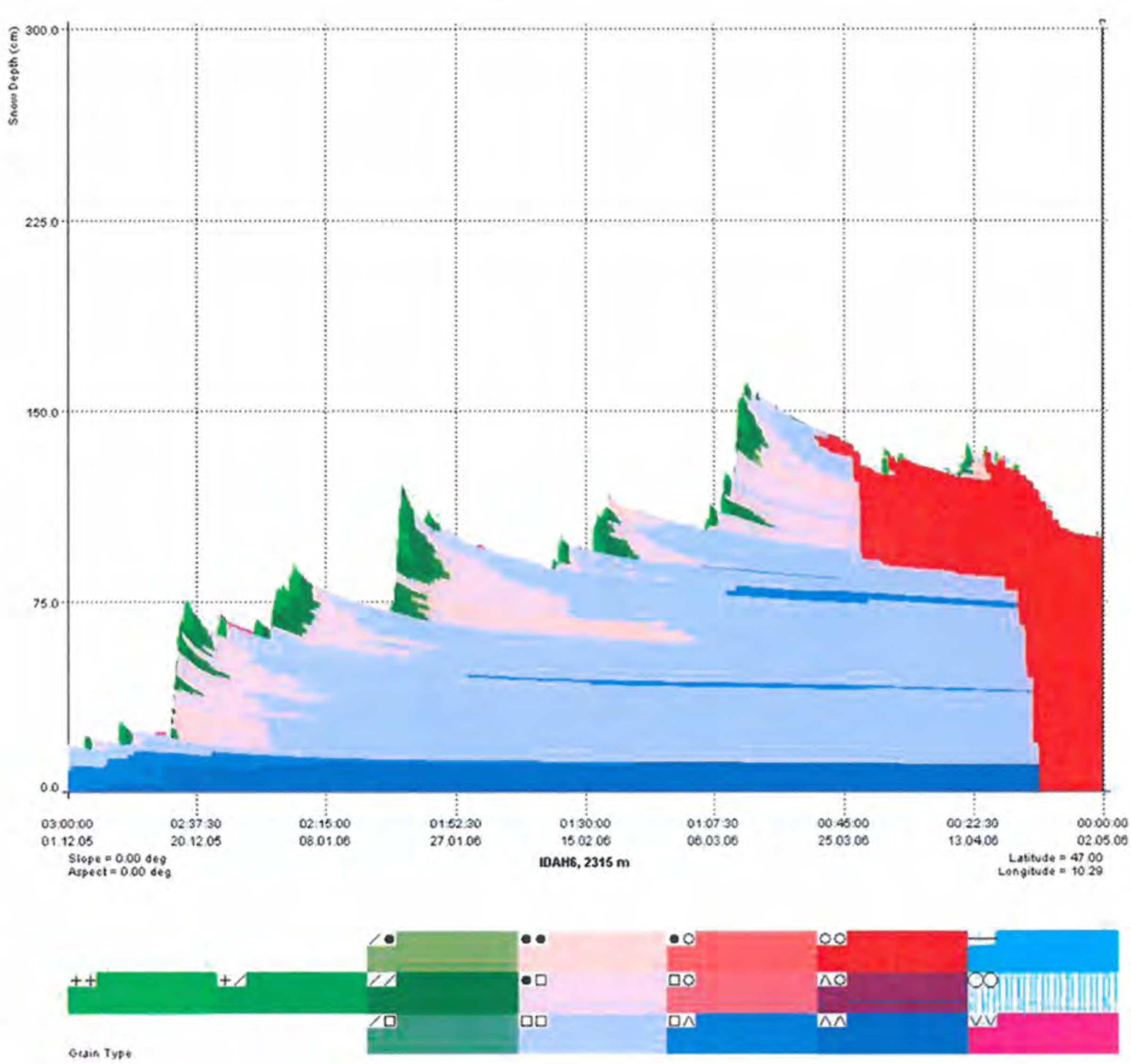
Simulation period: 18.11.2004 - 01.05.2005

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.8: SNOWPACK simulation (grain type), winter 2005/06



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

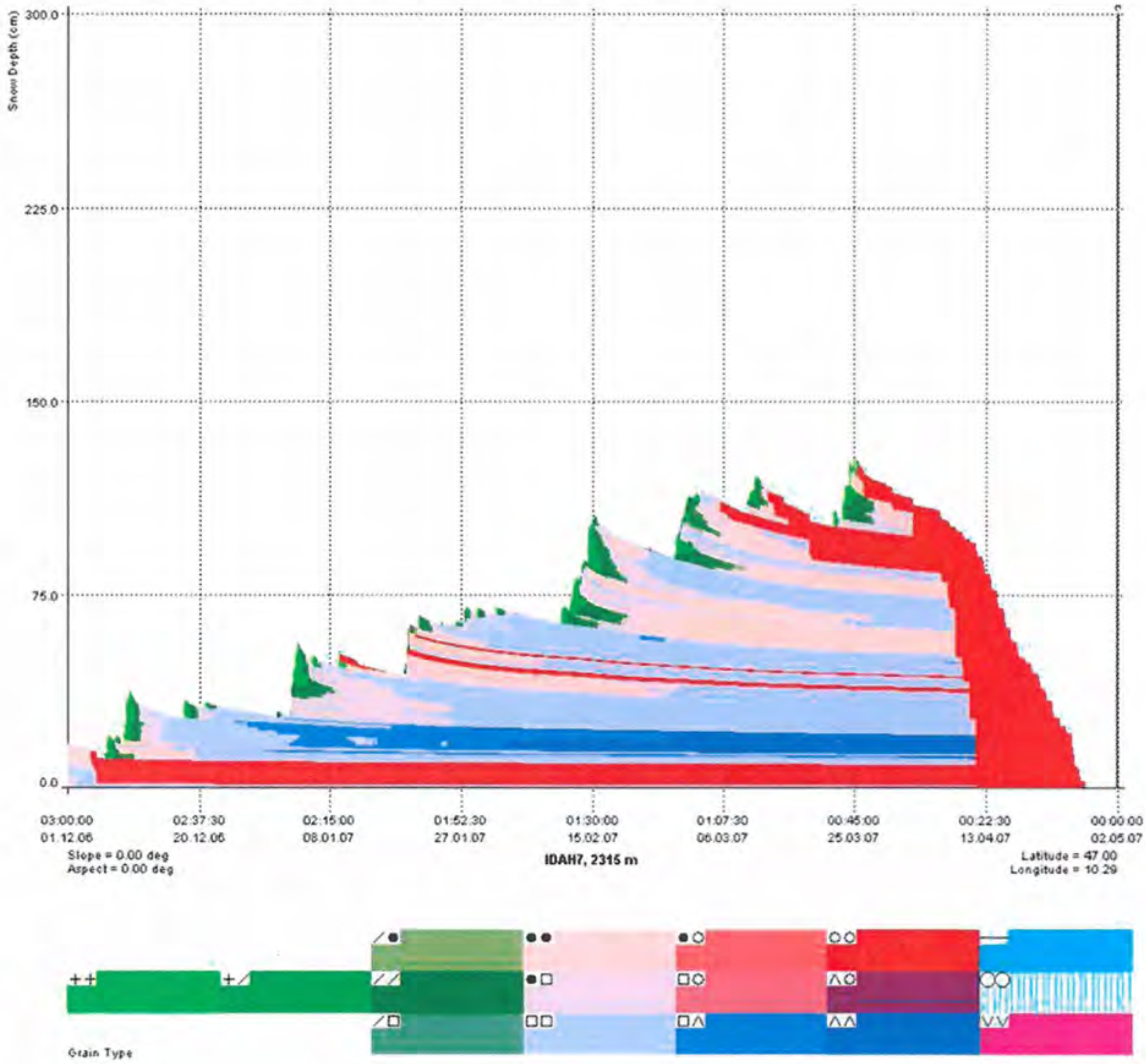
Simulation period: 19.11.2005 - 01.05.2006

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.9: SNOWPACK simulation (grain type), winter 2006/07



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

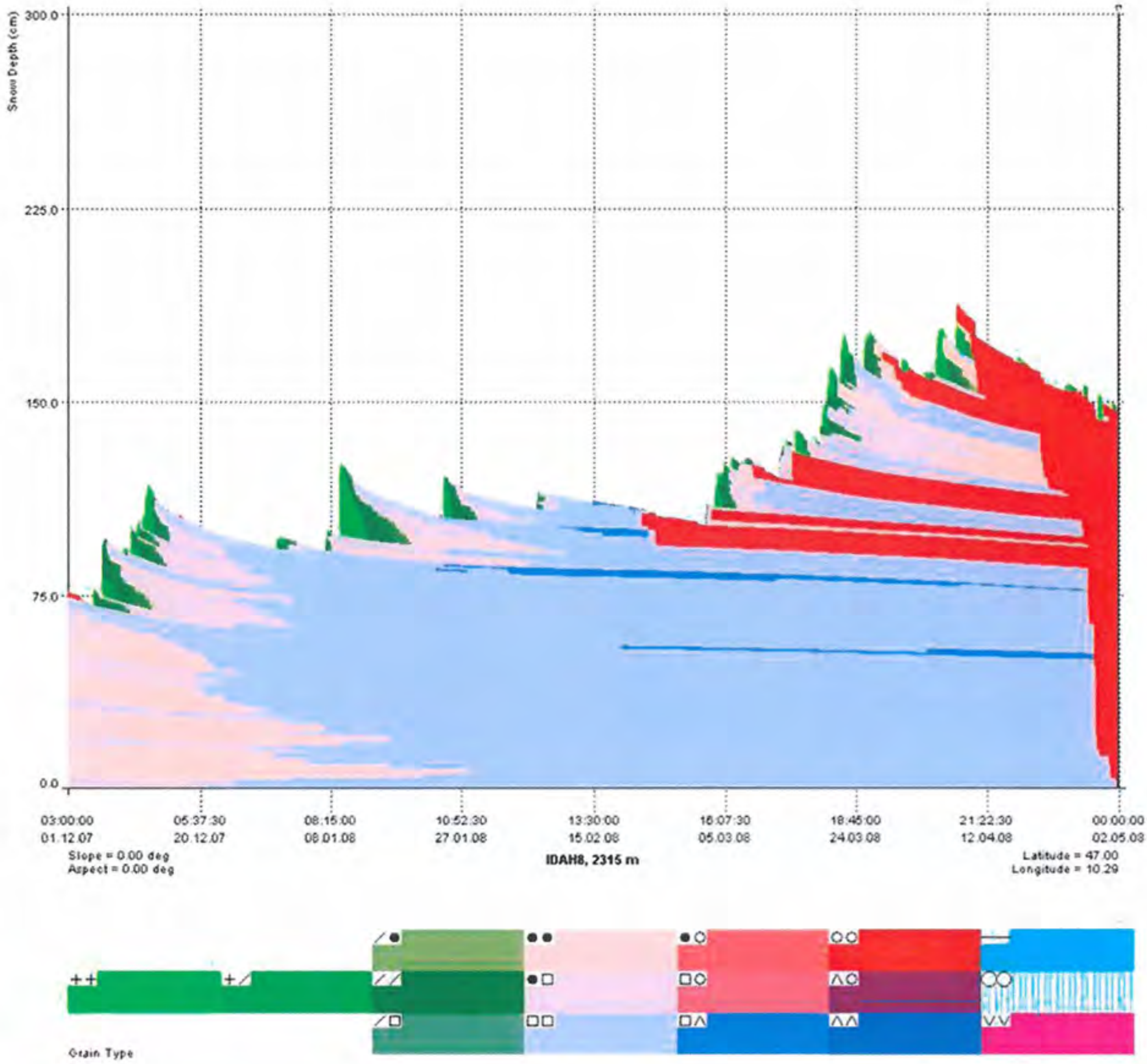
Simulation period: 20.11.2006 - 01.05.2007

Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C. Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

Figure C.10: SNOWPACK simulation (grain type), winter 2007/08



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA, RH, FF, DD, CL
Höllboden:	2147 m	ISWR, HS, TSS, TS0
Palinkopf:	2864 m	FF

Simulation period: 06.11.2007 - 01.05.2008

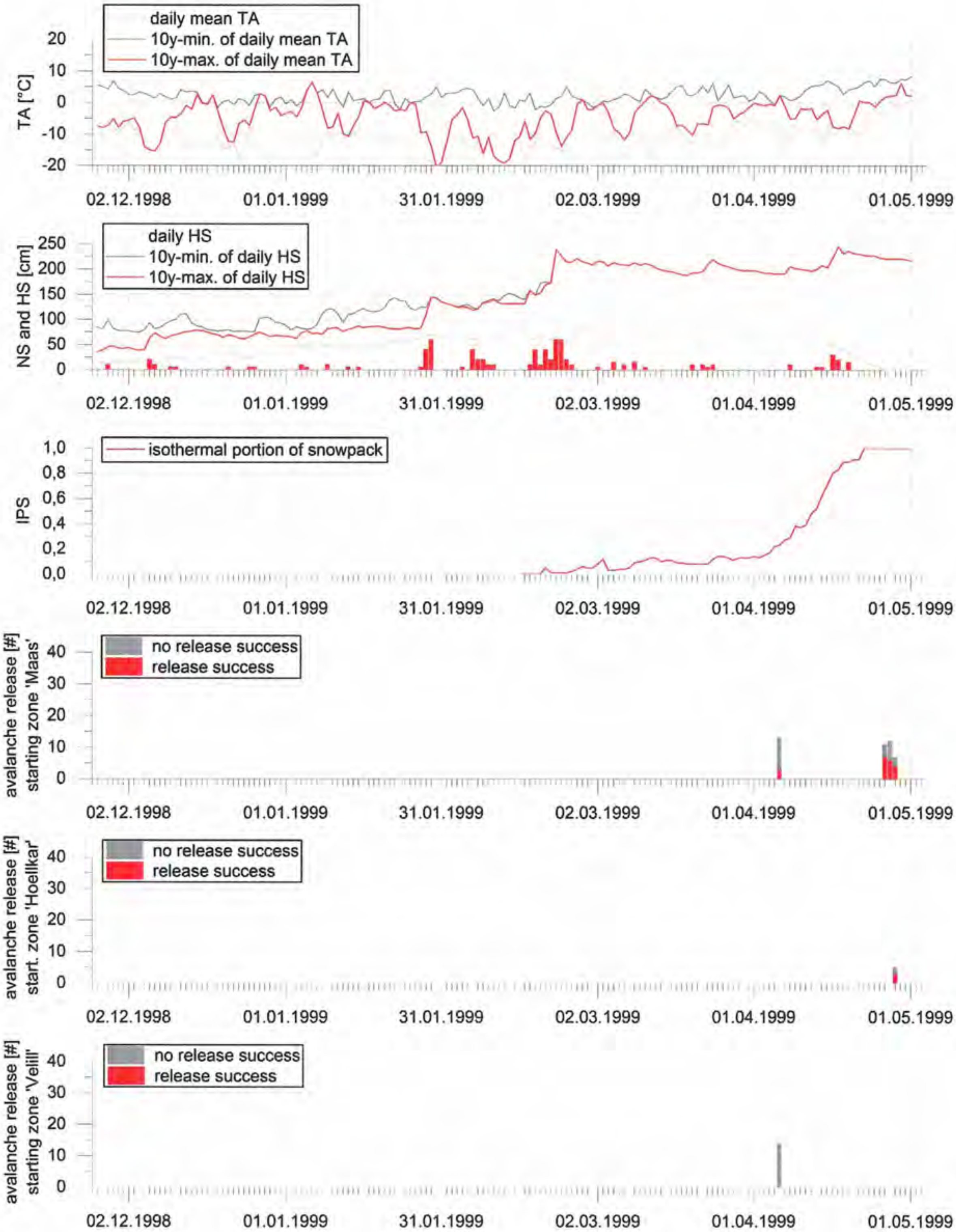
Model settings: Meteo step length: 30 min / Calculation step length: 15 min.

Upper boundary conditions: Neumann and Dirichlet boundary conditions with treshold value -1.0°C.

Atmospheric stability assumed. Bottom boundary conditions: Dirichlet boundary conditions.

Testing for blowing snow conditions activated. No inclusion of soil data.

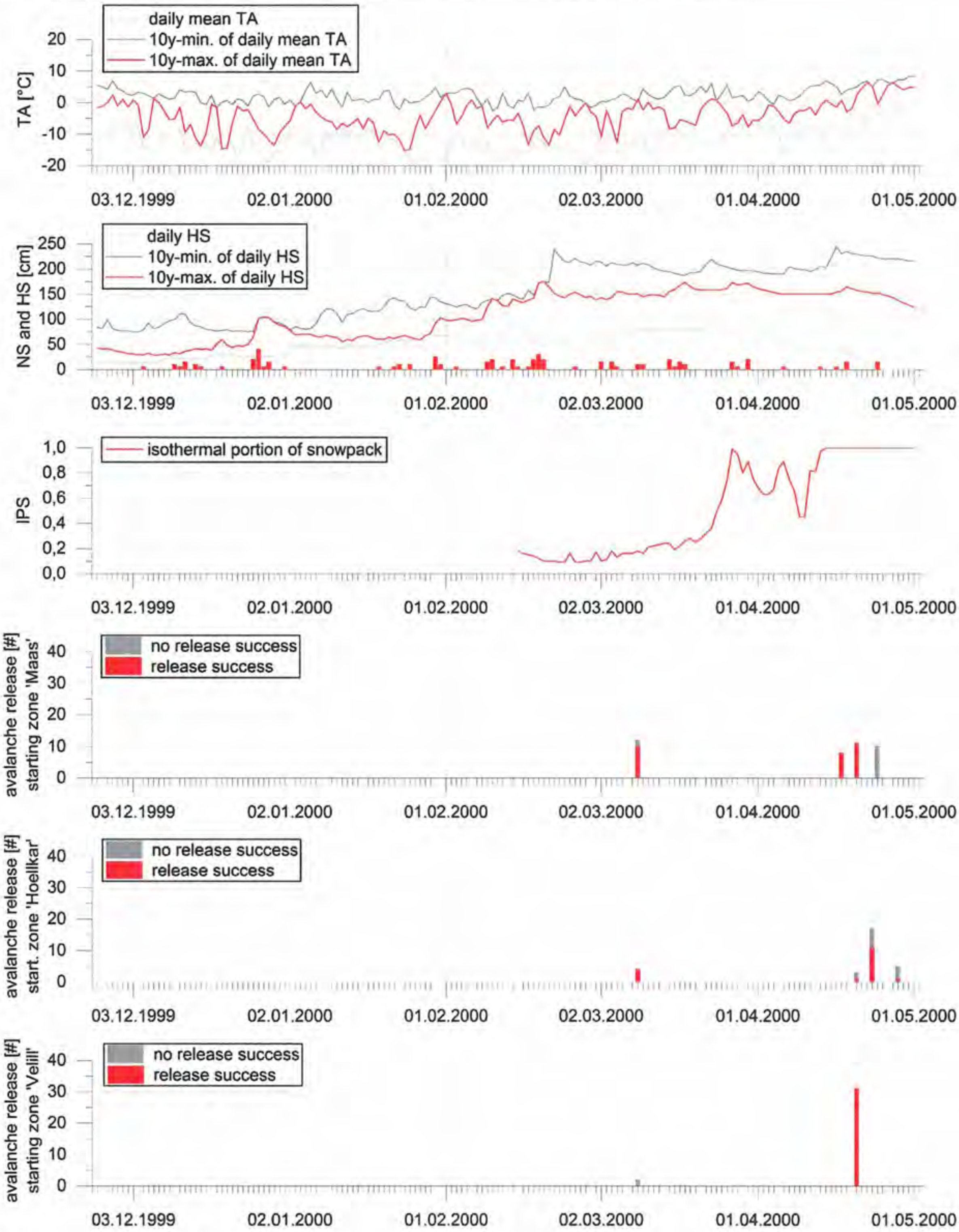
Figure C.11: Winter 1998/99: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

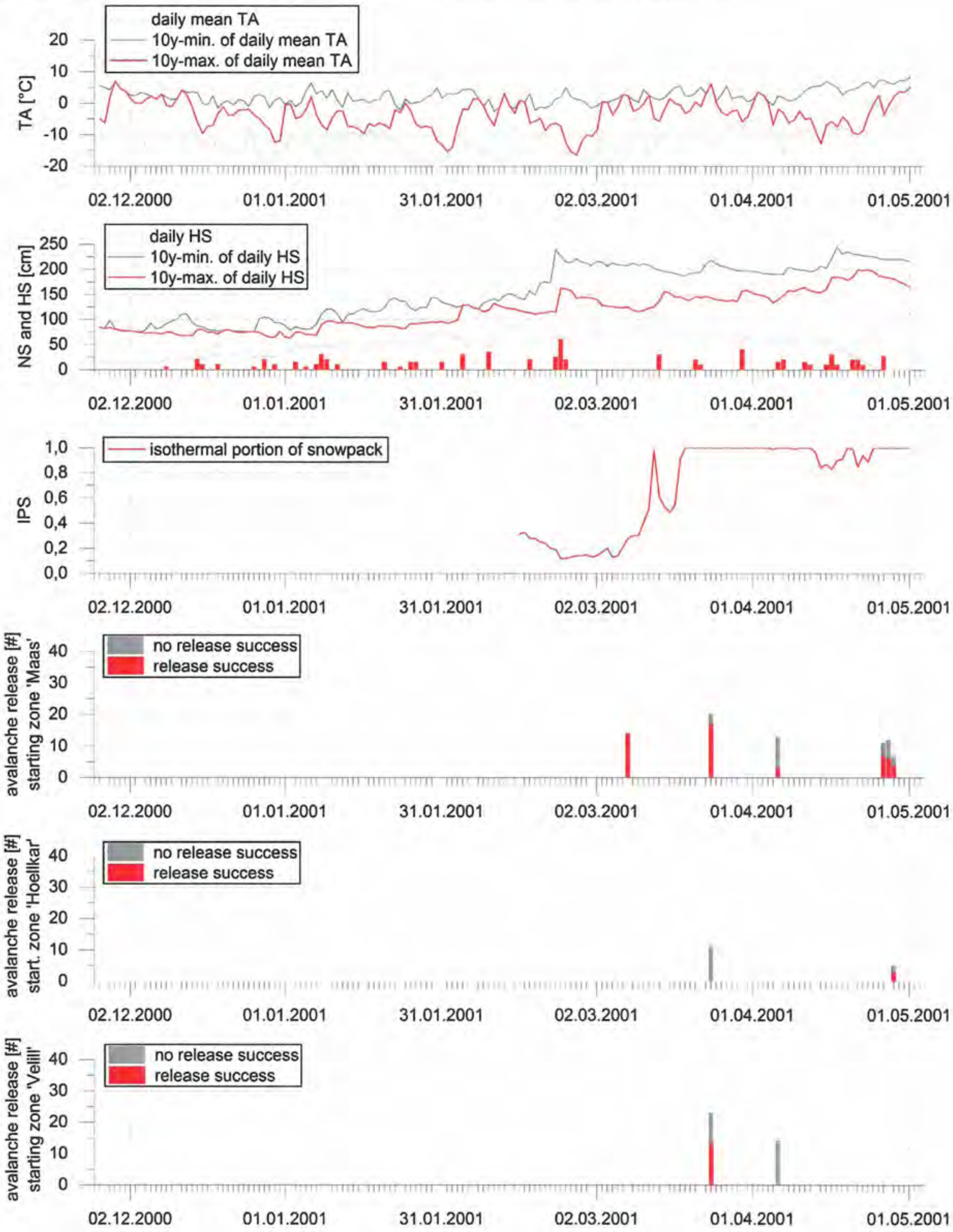
Figure C.12: Winter 1999/00: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

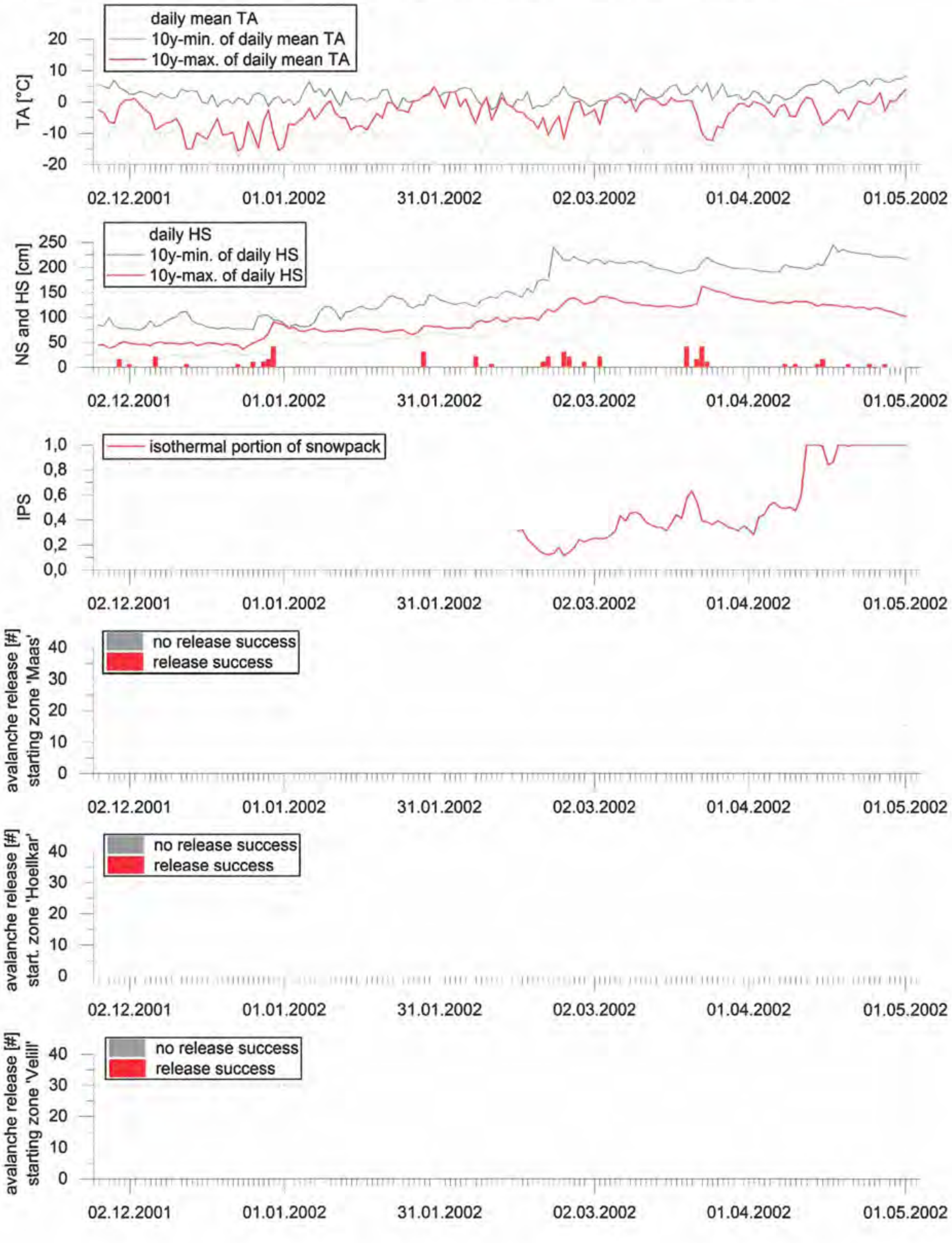
Figure C.13: Winter 2000/01: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

Figure C.14: Winter 2001/02: wet snow control operations and TA, HS, NS, IPS

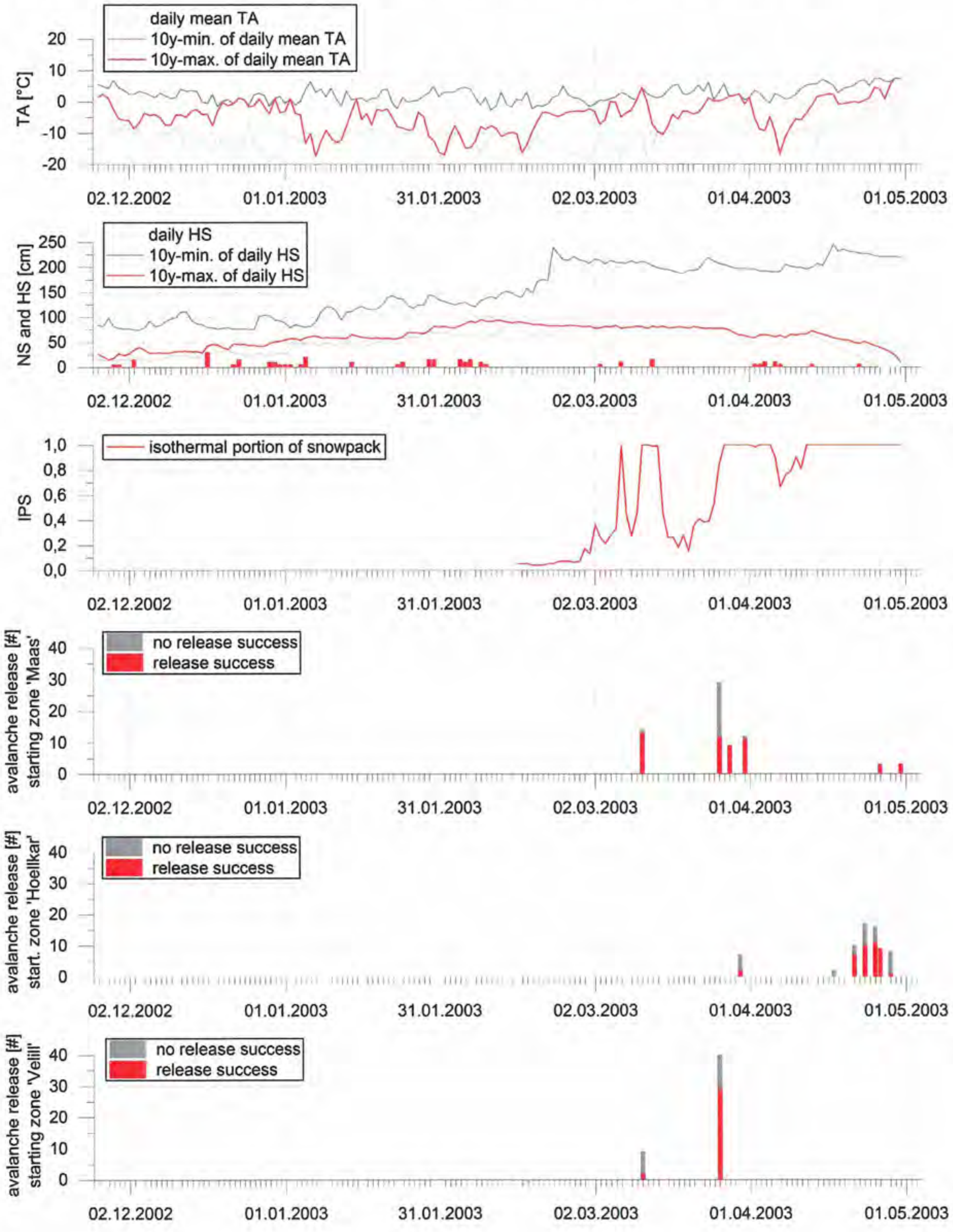


Input data was composed of data from the following weather stations:

Idalpe: 2315 m TA

Höllboden: 2147 m NS, HS, IPS (SNOWPACK)

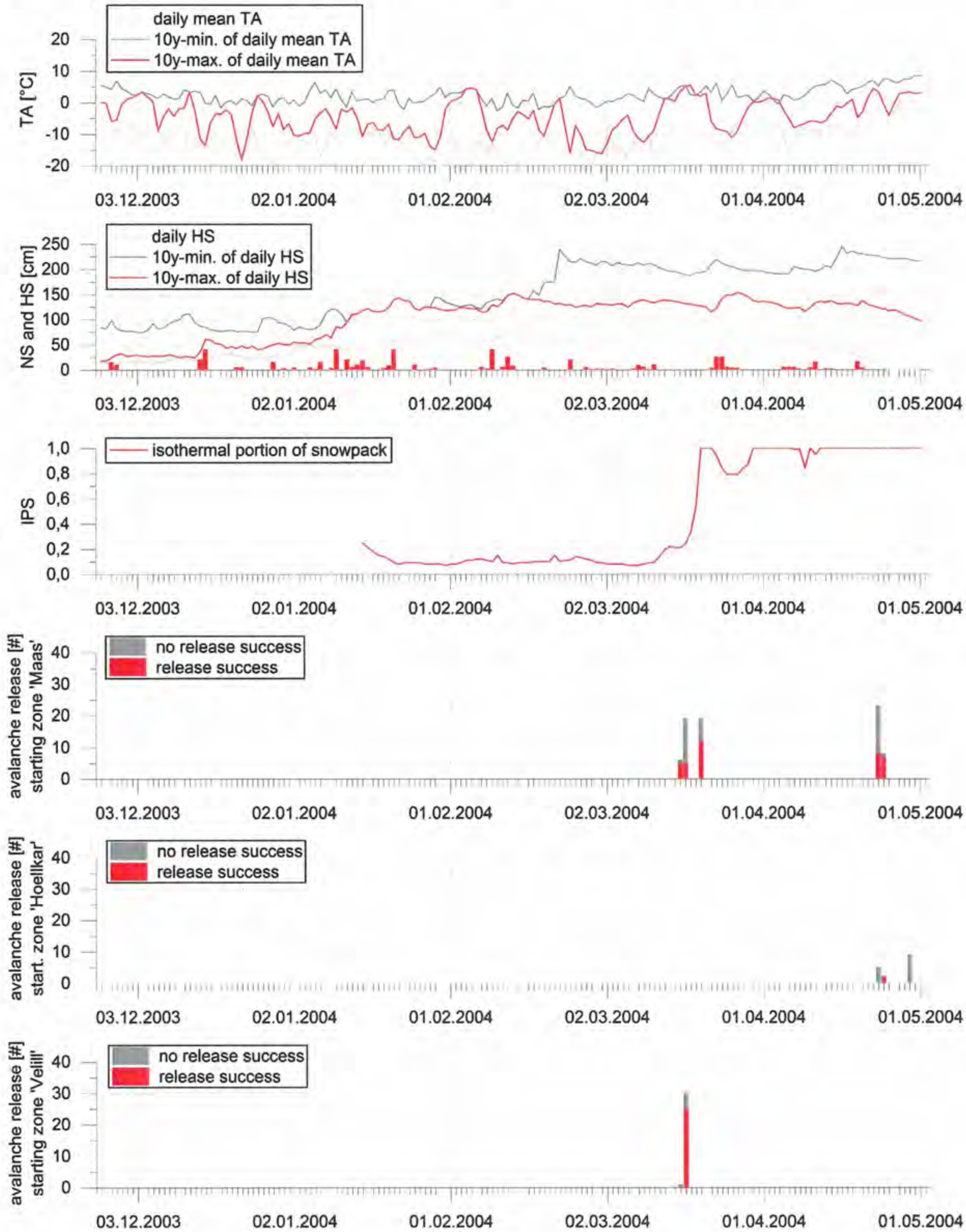
Figure C.15: Winter 2002/03: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

Figure C.16: Winter 2003/04: wet snow control operations and TA, HS, NS, IPS

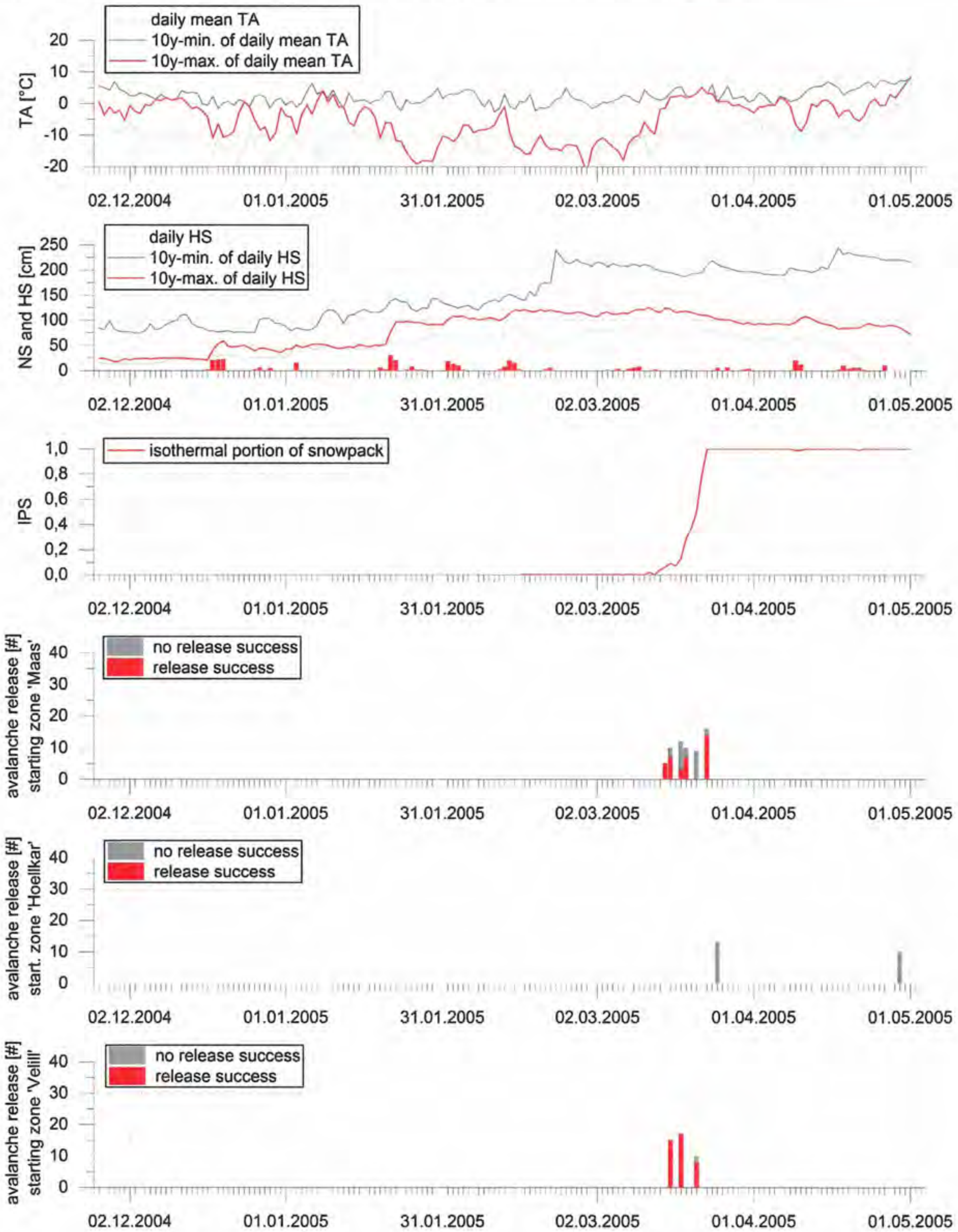


Input data was composed of data from the following weather stations:

Idalpe: 2315 m TA

Höllboden: 2147 m NS, HS, IPS (SNOWPACK)

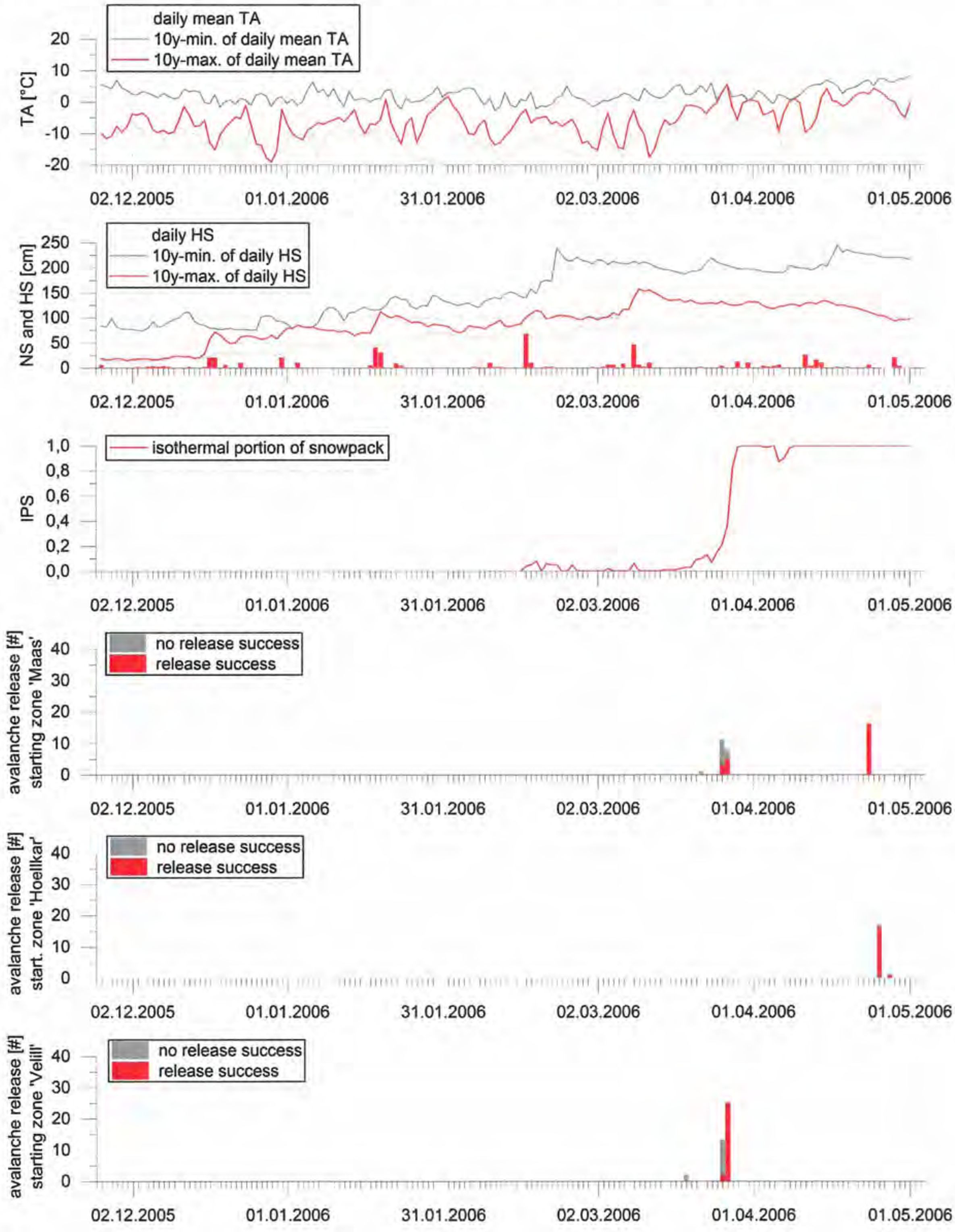
Figure C.17: Winter 2004/05: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

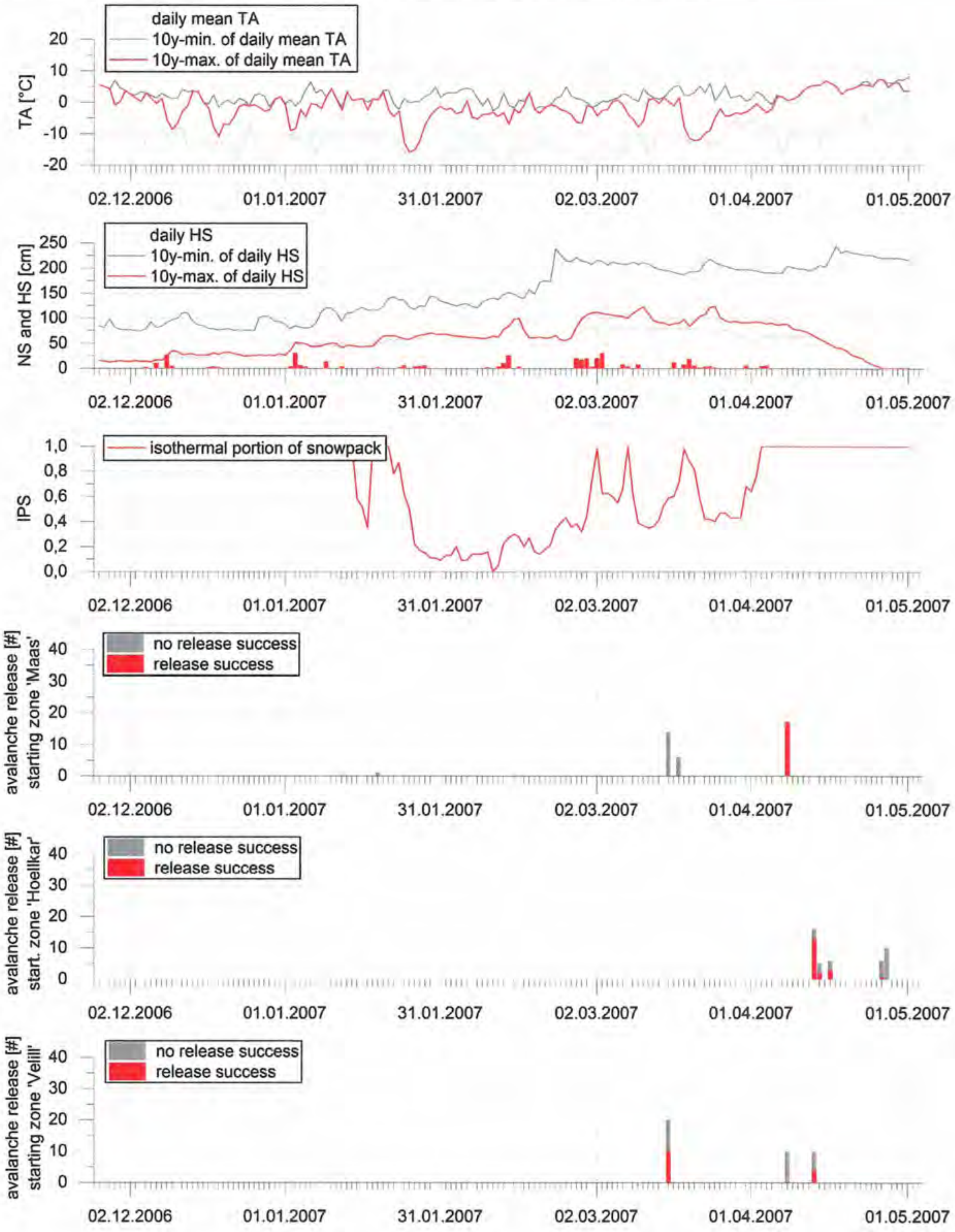
Figure C.18: Winter 2005/06: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

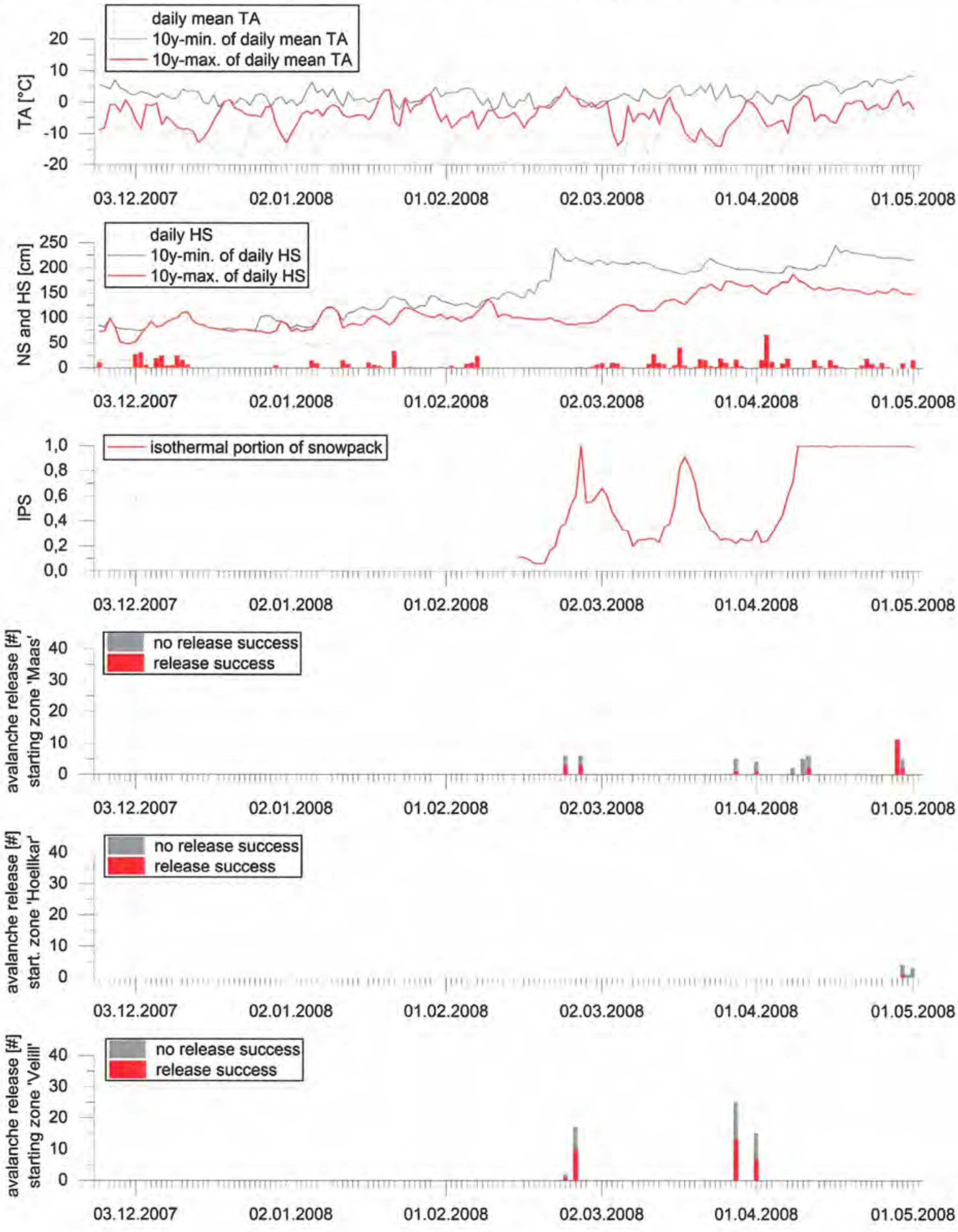
Figure C.19: Winter 2006/07: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

Figure C.20: Winter 2007/08: wet snow control operations and TA, HS, NS, IPS



Input data was composed of data from the following weather stations:

Idalpe:	2315 m	TA
Höllboden:	2147 m	NS, HS, IPS (SNOWPACK)

Figure C.21: Control operations (PFP): boxplots of mean and minimum TA Idalpe

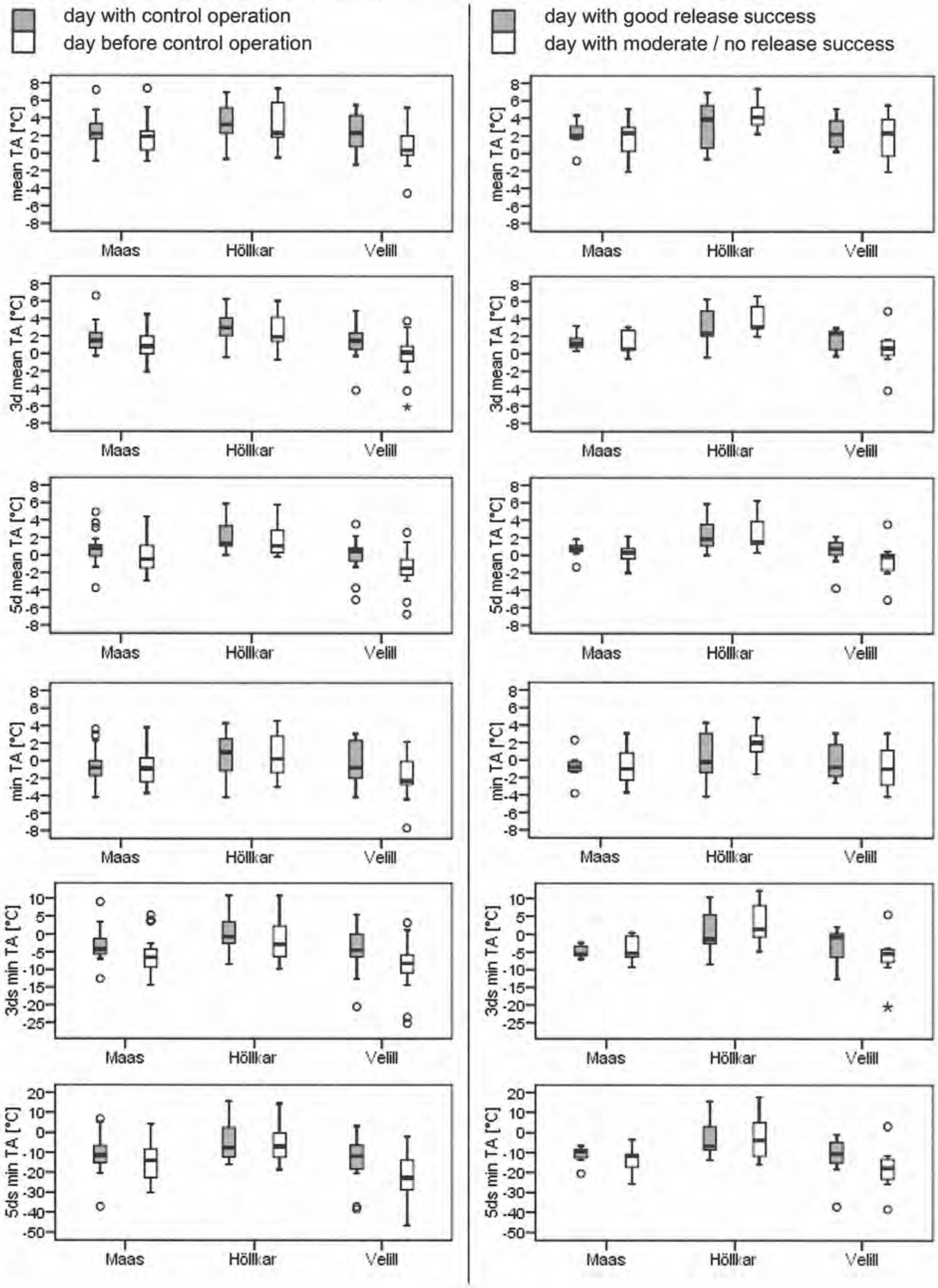


Figure C.22: Control operations (PFP): boxplots of maximum TA Idalpe

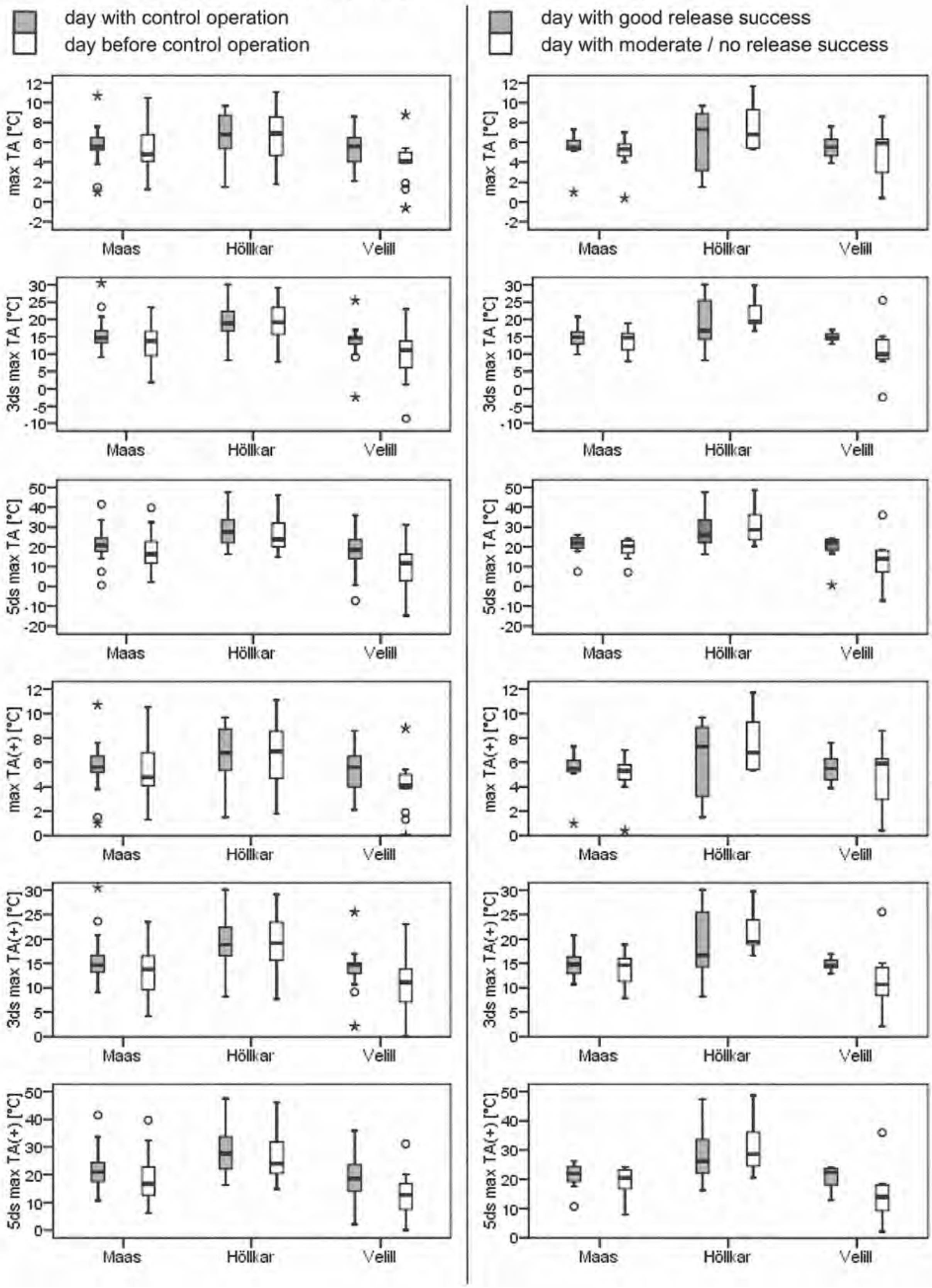


Figure C.23: Control operations (PFP): boxplots of mean and minimum TA Palinkopf

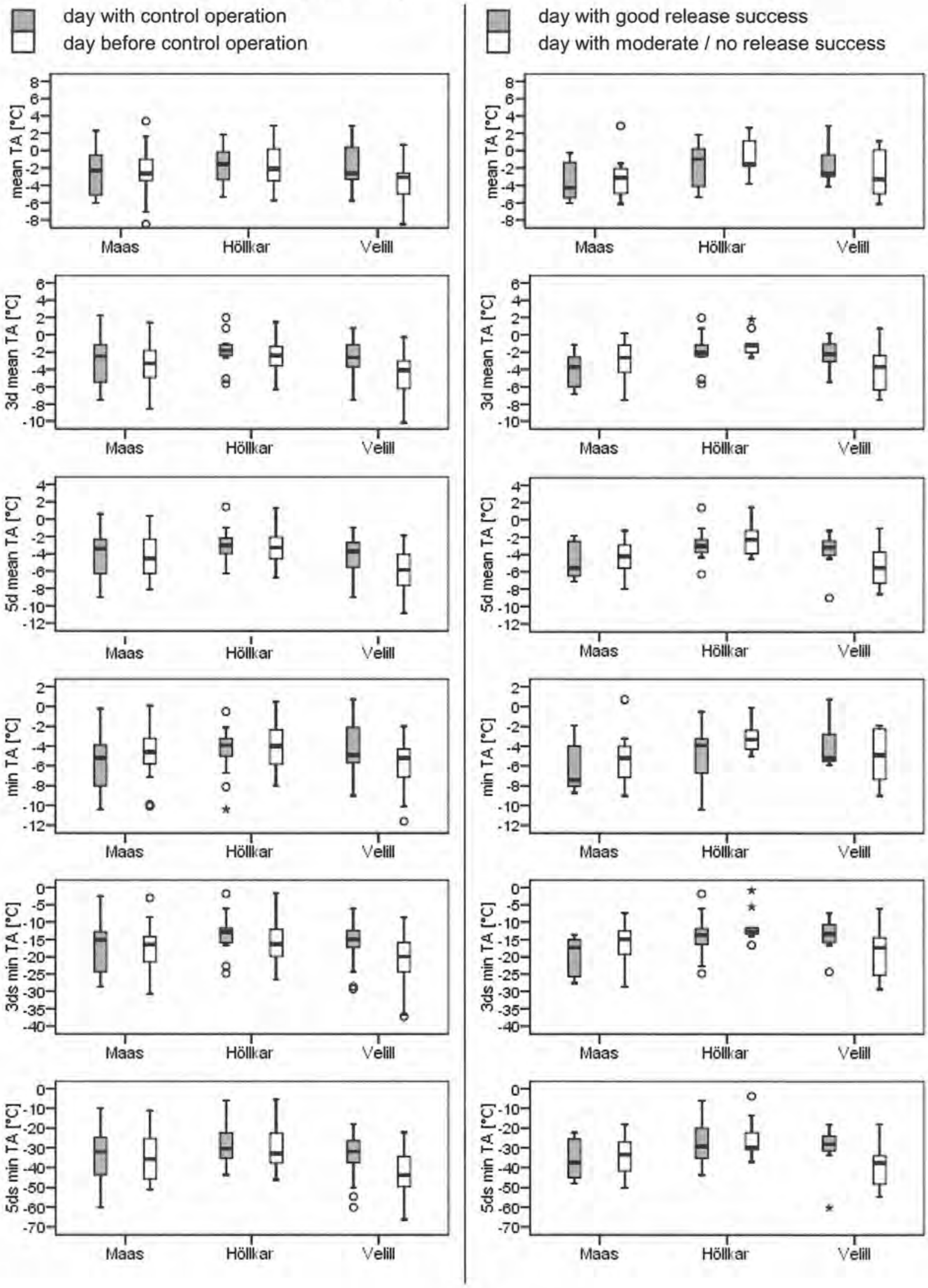


Figure C.24: Control operations (PFP): boxplots of maximum TA Palinkopf

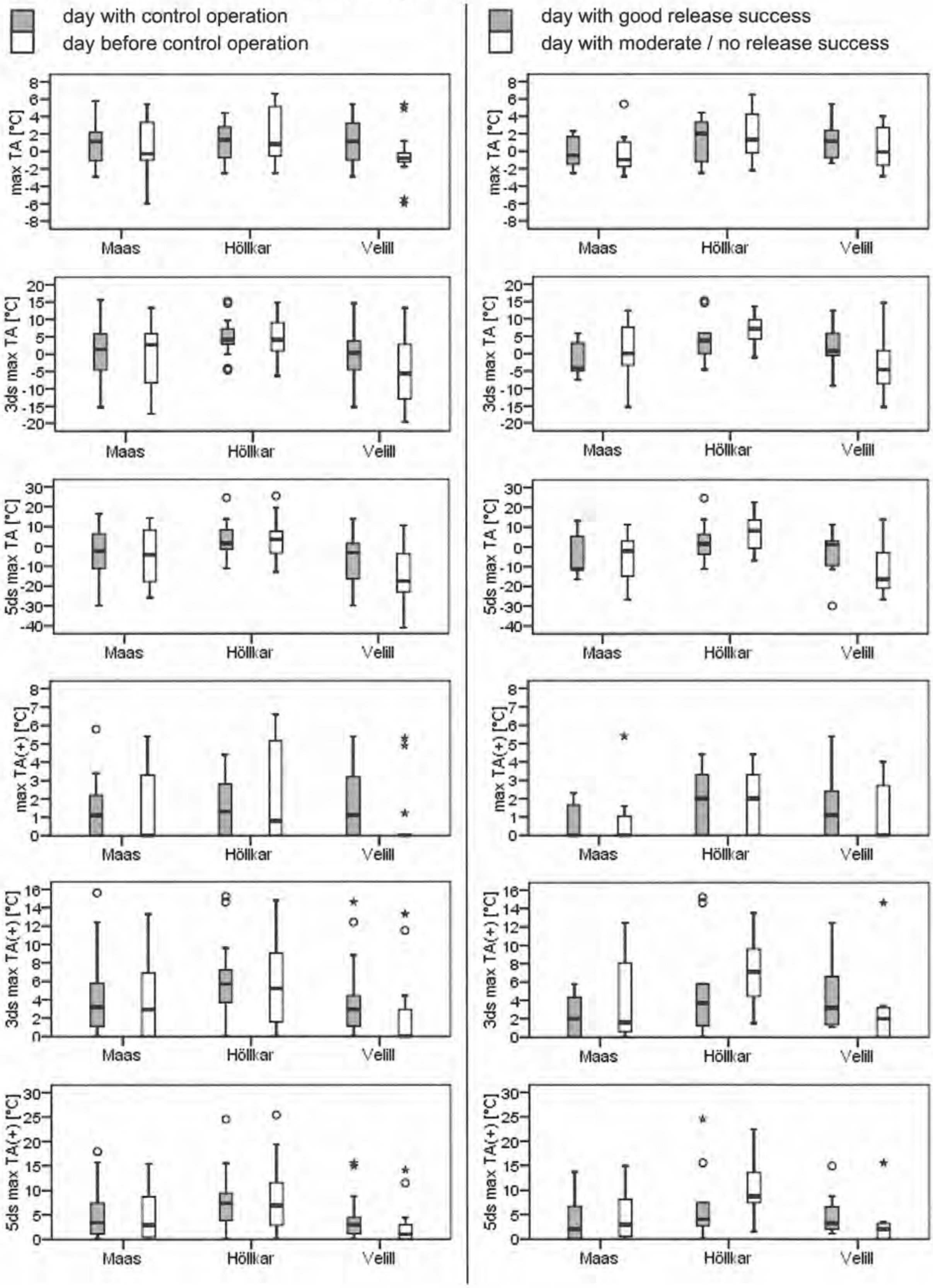


Figure C.25: Control operations (PFP): boxplots of mean and minimum TA starting zone

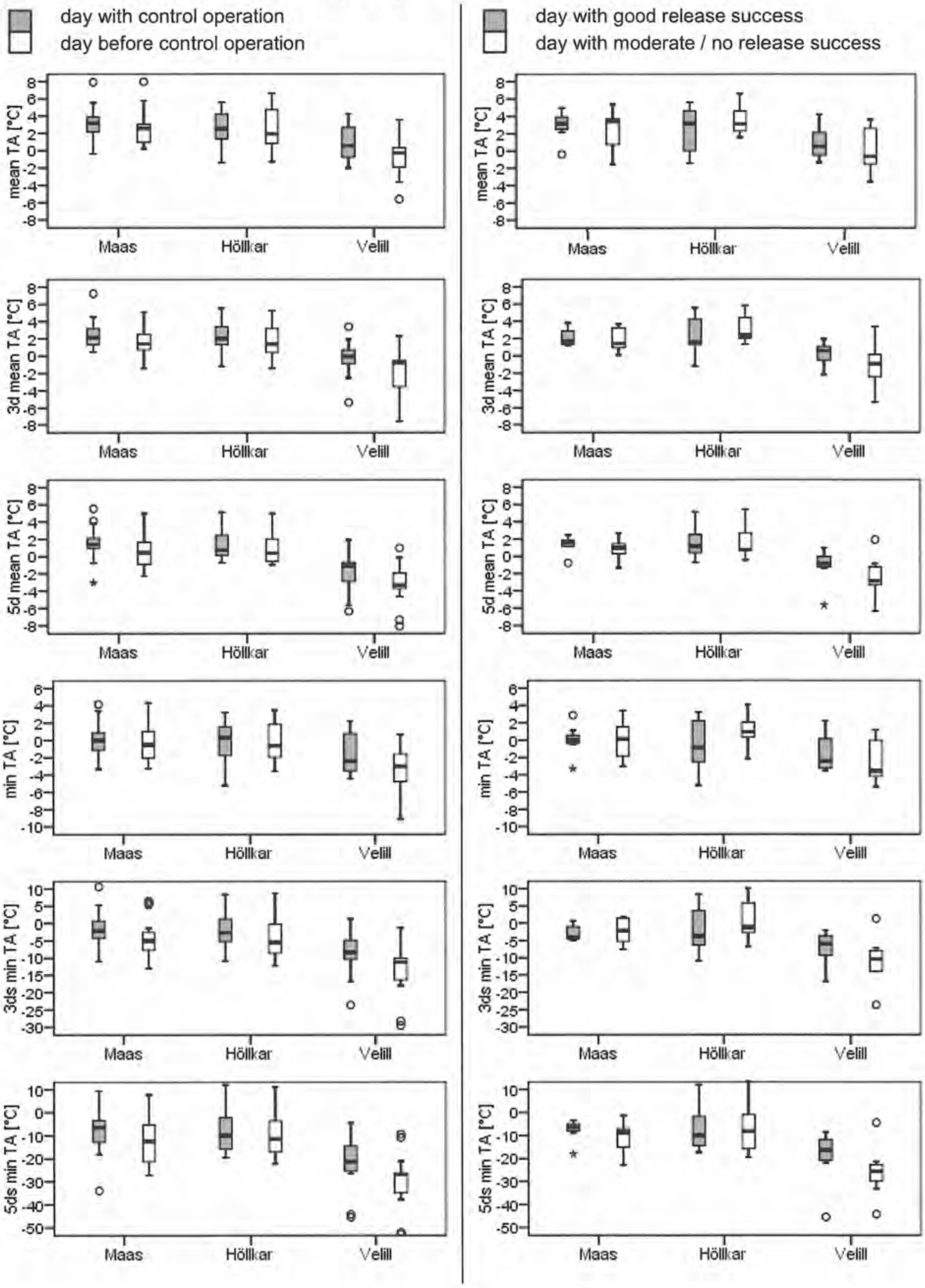


Figure C.26: Control operations (PFP): boxplots of maximum TA starting zone

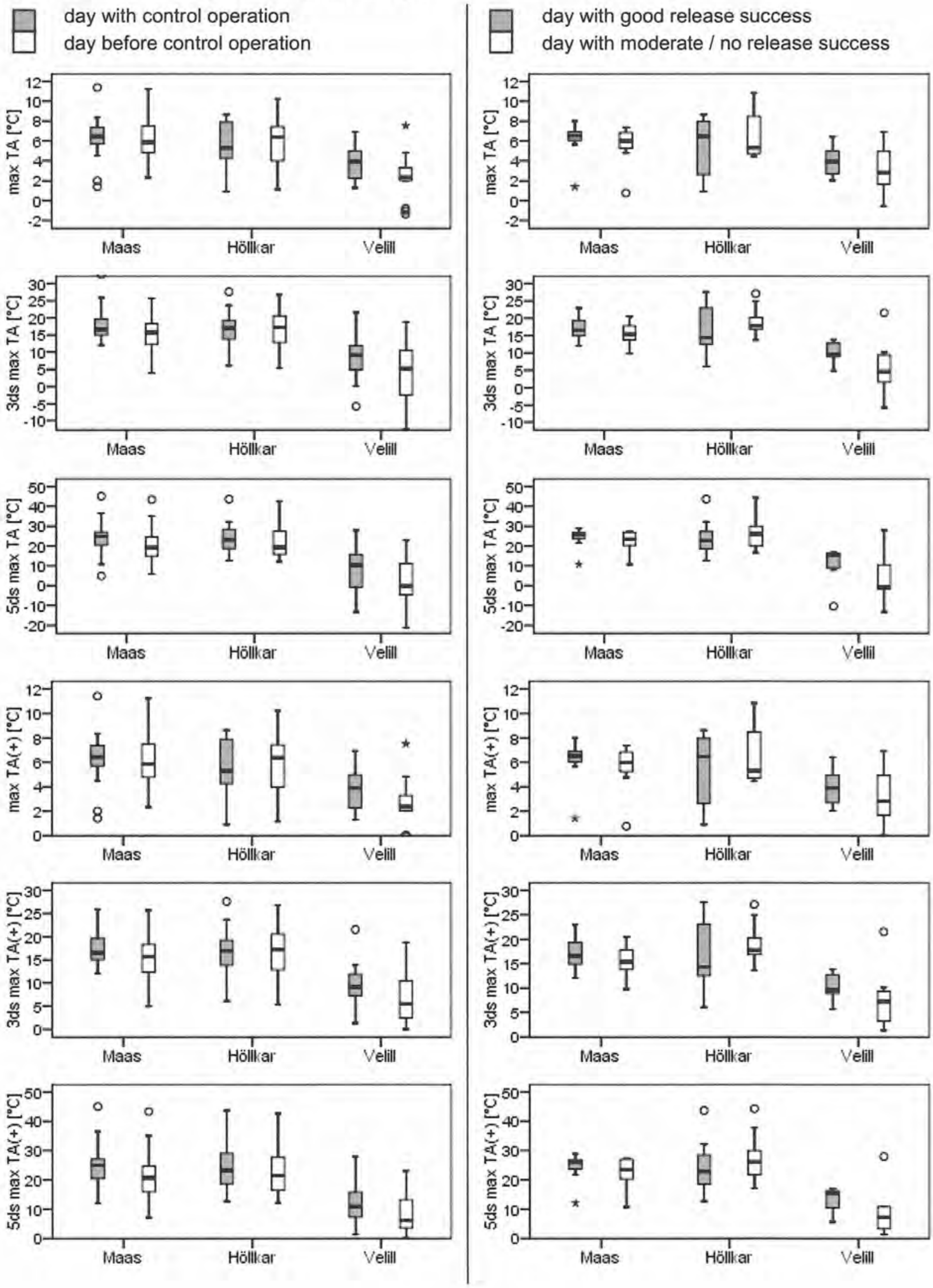


Figure C.27: Control operations (PFP): boxplots of mean RH Idalpe

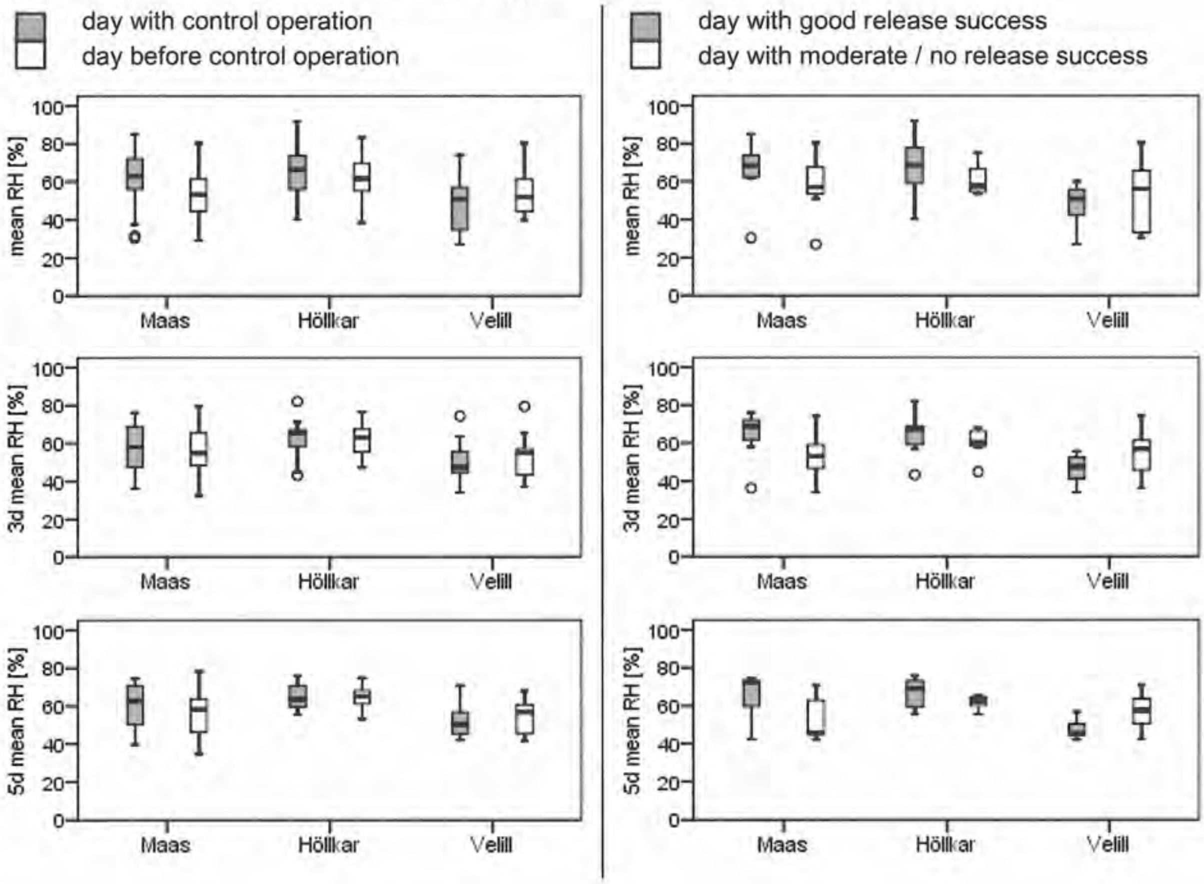


Figure C.28: Control operations (PFP): boxplots of mean RH Palinkopf

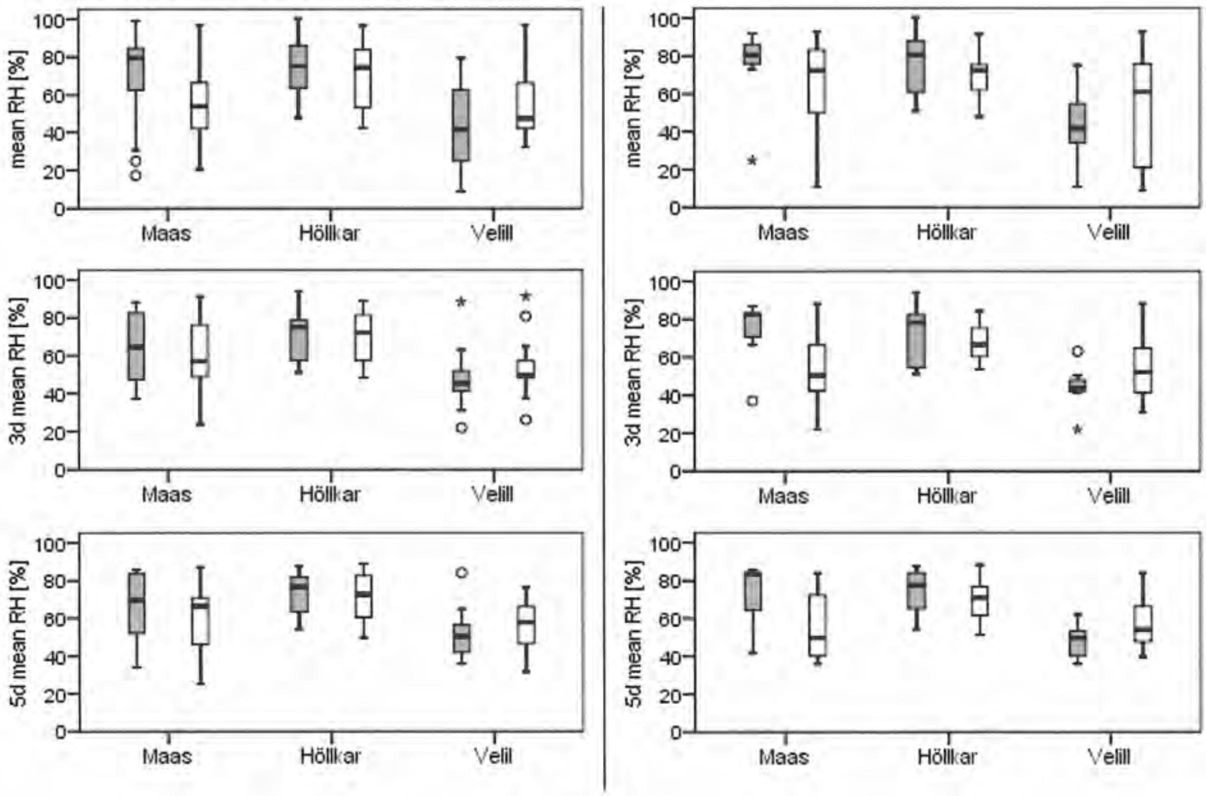


Figure C.29: Control operations (PFP): boxplots of mean CL Idalpe

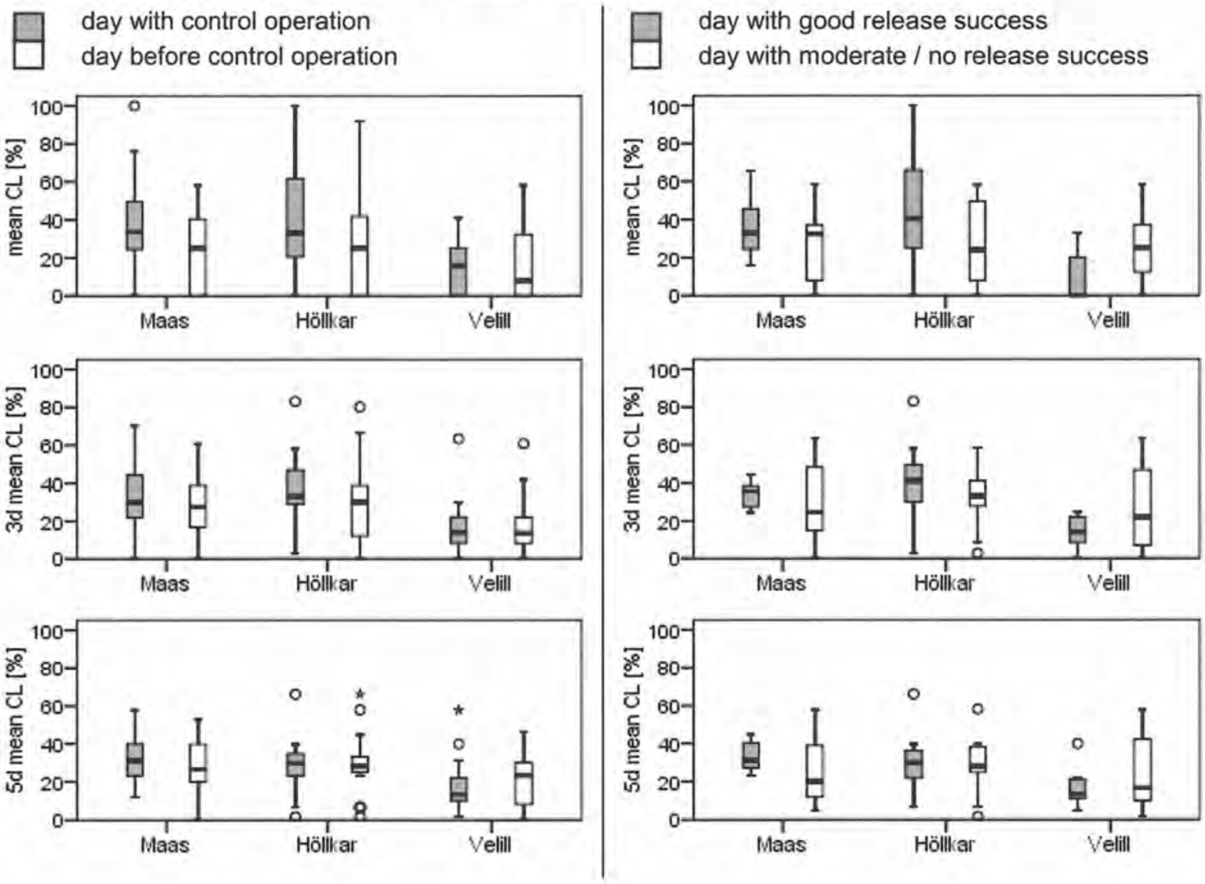


Figure C.30: Control operations (PFP): boxplots of minimum TSS Höllboden

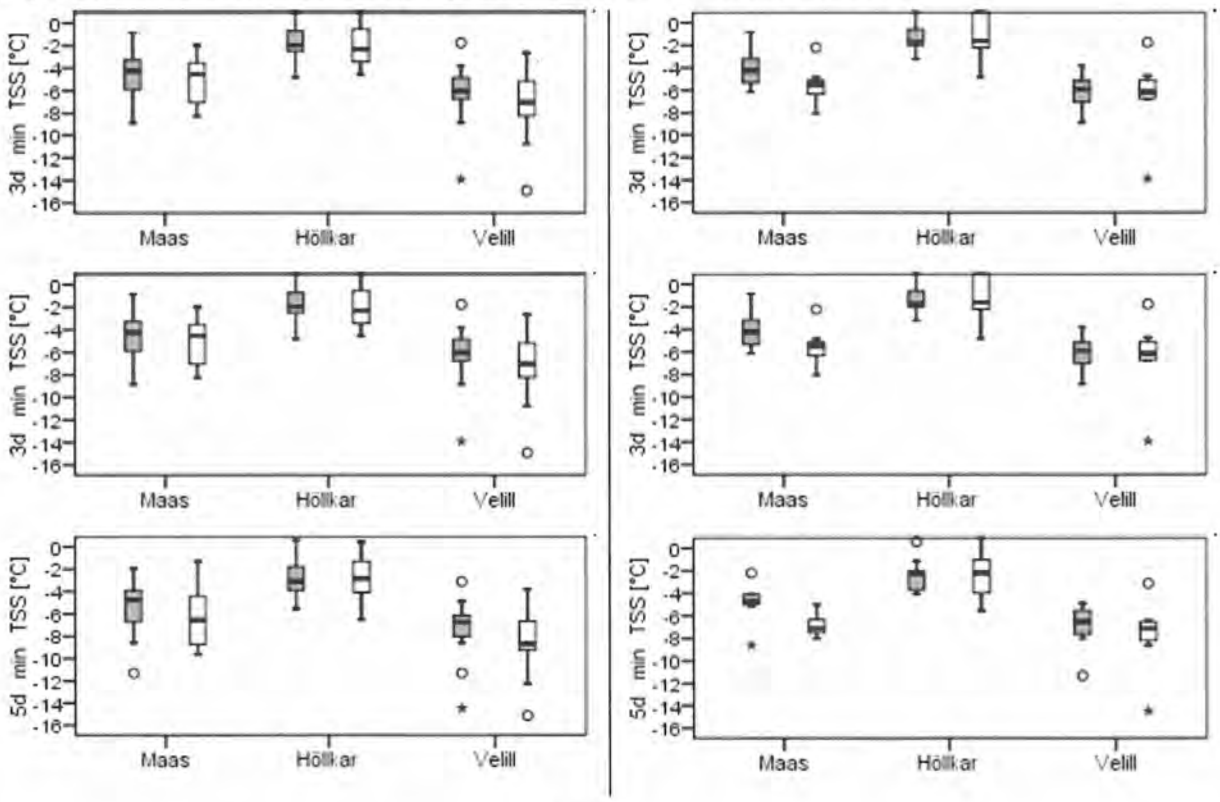


Figure C.31: Control operations (PFP): boxplots of mean HS Höllboden

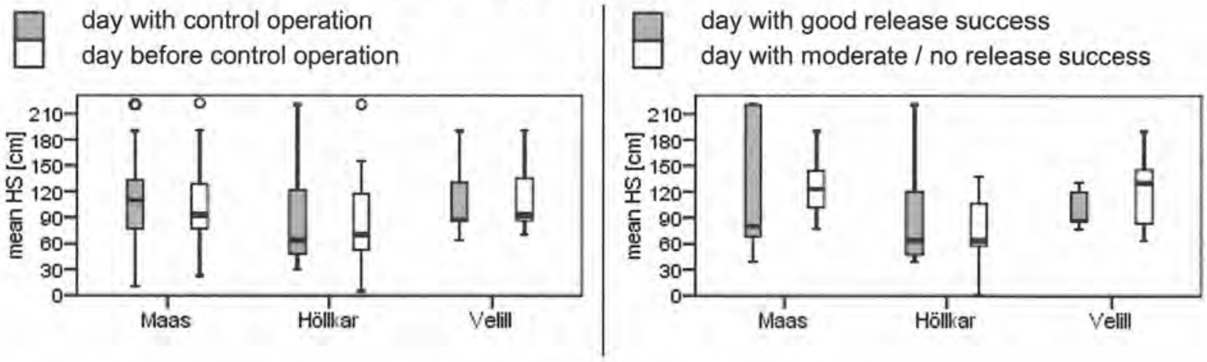


Figure C.32: Control operations (PFP): boxplots of mean IPS Höllboden

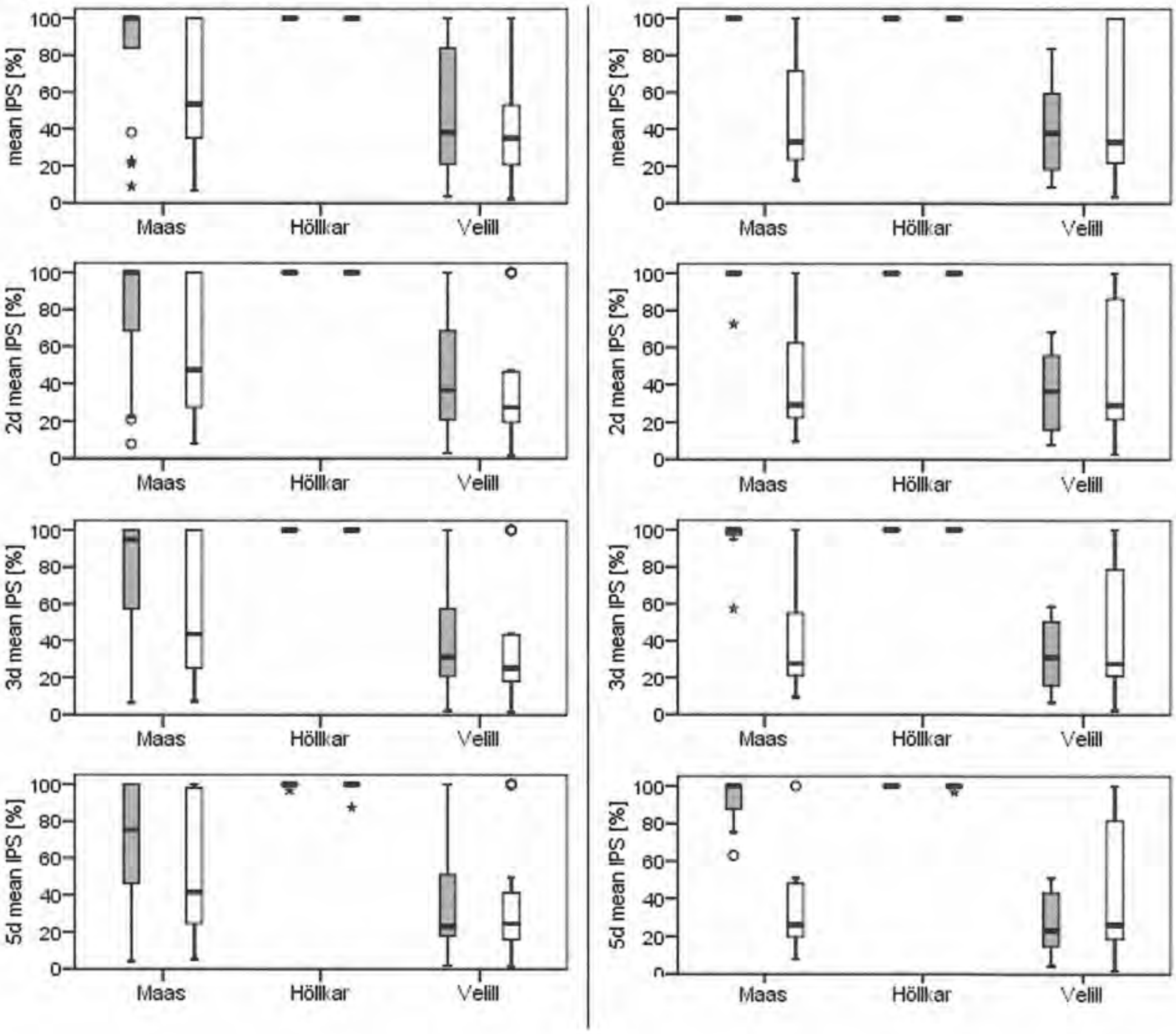


Figure C.33: Control operations (PFP): boxplots of daily sum and maximum ISWR Höllboden

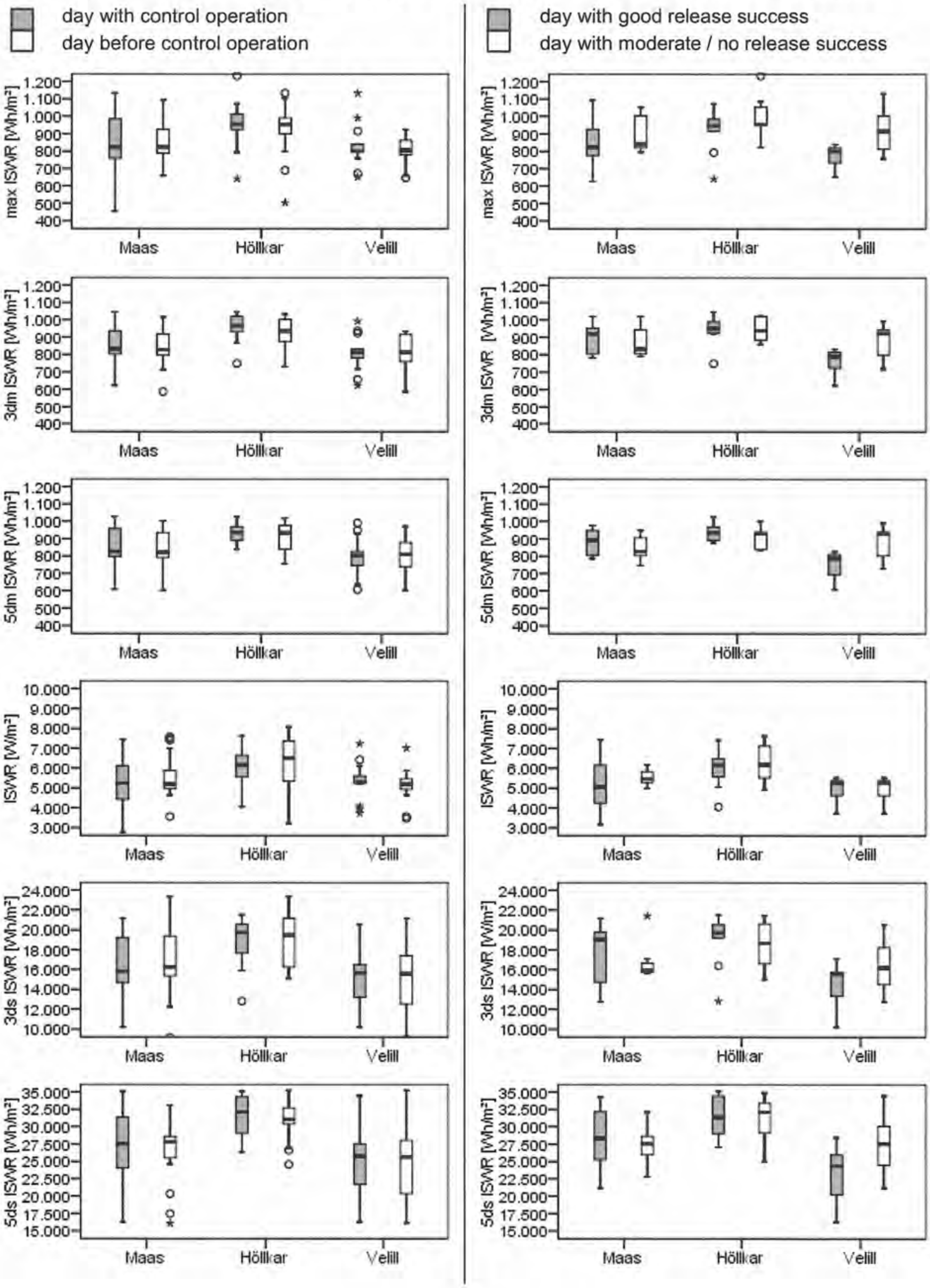


Figure C.34: Control operations (PFP): boxplots of daily sum ISWR starting zone

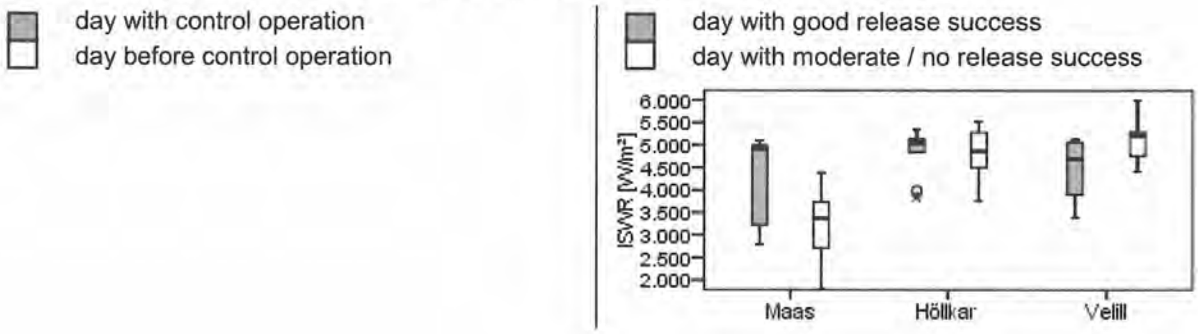


Figure C.35: Control operations (PFP): boxplots of mean FF Idalpe

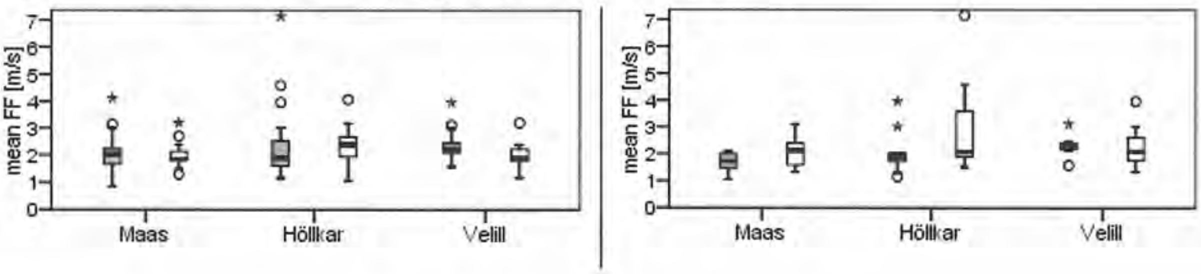


Figure C.36: Control operations (PFP): boxplots of mean FF Palinkopf

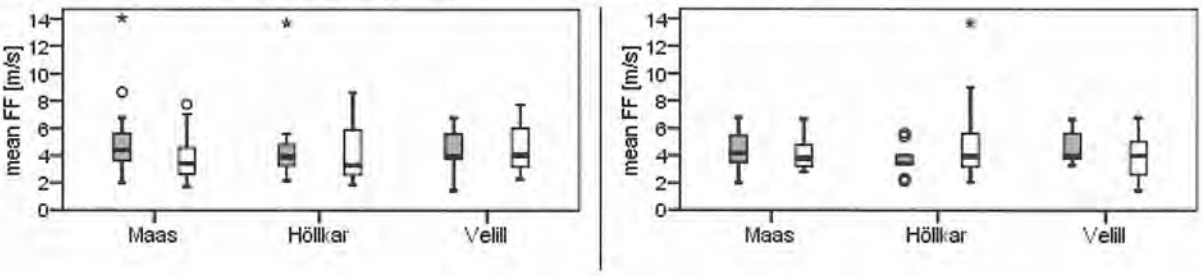
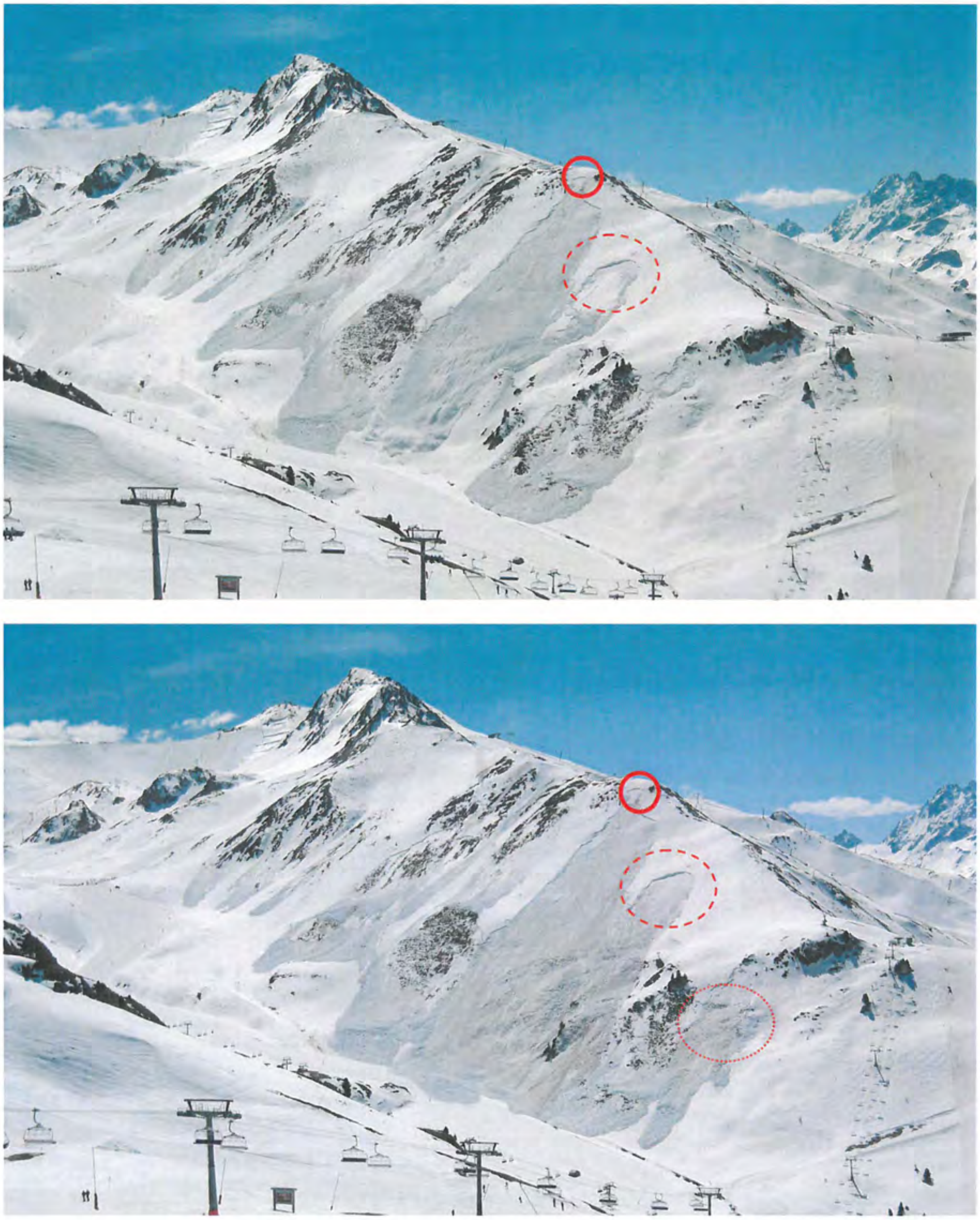


Figure C.37: Pictures of released wet slab avalanches in the starting zone Maas (NW)

Successfully triggered wet slab avalanches in the starting zone Maas, Ischgl. The starting zone endangers the main slope down to the village of Ischgl. Usually, several wet snow avalanche cycles in spring time enforce control operations in this starting zone (photos: avalanche control service Ischgl).

Figure C.38: Pictures of released wet slab avalanches in the starting zone Höllkar (NE)



Successful triggering of a wet slab avalanche at the starting zone Höllkar, Ischgl. Often it takes some days of continuous test releases to be successful and to empty the starting zone. The avalanche triggered two more avalanches: one just adjacent (middle), the other about 300 m away (right). The total closure time of the ski slope was only about 20 minutes (photos: Martin Oberhammer).

release point   secondary release   remote release

Figure C.39: Pictures of released wet loose snow avalanches in the starting zone Velill (SW)

Successfully controlled wet loose snow avalanches from the helicopter at the starting zone Vellil, Ischgl. These starting zones endanger a ski slope in the valley bottom. Many release points have to be triggered to empty the starting zone (photos: Martin Oberhammer).

Table C.1: Snowprofile dataset

	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08
Snowprofiles (SP) in N aspect										
number of SP [#]	6	3	9	5	5	7	5	5	6	5
min. sealevel of SP [m]	2500	2400	2200	2480	2200	2500	2310	2500	2130	2220
max. sealevel of SP [m]	2700	2560	2700	2650	2750	2700	2595	2570	2720	2560
mean sealevel of SP [m]	2586	2490	2491	2542	2495	2563	2515	2532	2478	2416
Snowprofiles (SP) in NE aspect										
number of SP [#]	2	3	1	2	4	0	2	1	1	3
min. sealevel of SP [m]	2250	2494	1900	2434	2320		2500	2420	2490	2260
max. sealevel of SP [m]	2320	2600	1900	2700	2750		2687	2420	2490	2500
mean sealevel of SP [m]	2285	2535	1900	2567	2522		2594	2420	2490	2367
Snowprofiles (SP) in E aspect										
number of SP [#]	4	3	2	2	2	2	1	2	3	1
min. sealevel of SP [m]	2300	2300	2300	2540	2350	2300	2822	2270	2300	2480
max. sealevel of SP [m]	2600	2540	2350	2600	2485	2485	2822	2500	2500	2480
mean sealevel of SP [m]	2455	2380	2325	2570	2417	2392	2822	2385	2430	2480
Snowprofiles (SP) in SE-SW aspect										
number of SP [#]	4	3	3	7	3	2	2	1	0	1
min. sealevel of SP [m]	2450	2550	2450	2290	2410	2500	2500	2540		2576
max. sealevel of SP [m]	2550	2600	2700	2700	2600	2790	2616	2540		2576
mean sealevel of SP [m]	2500	2567	2583	2431	2487	2645	2558	2540		2576
Snowprofiles (SP) in W aspect										
number of SP [#]	2	5	2	3	3	3	3	2	1	
min. sealevel of SP [m]	2200	2300	2400	2300	2450	2380	2230	2550	2500	
max. sealevel of SP [m]	2550	2580	2700	2620	2600	2750	2570	2750	2500	
mean sealevel of SP [m]	2375	2406	2550	2487	2500	2577	2367	2650	2500	
Snowprofiles (SP) in NW aspect										
number of SP [#]	2	2	2	4	1	4	5	5	1	1
min. sealevel of SP [m]	2350	2460	2300	2550	2510	2250	2043	2050	2385	2500
max. sealevel of SP [m]	2650	2495	2500	2660	2510	2550	2545	2620	2385	2500
mean sealevel of SP [m]	2500	2478	2400	2600	2510	2375	2336	2350	2385	2500

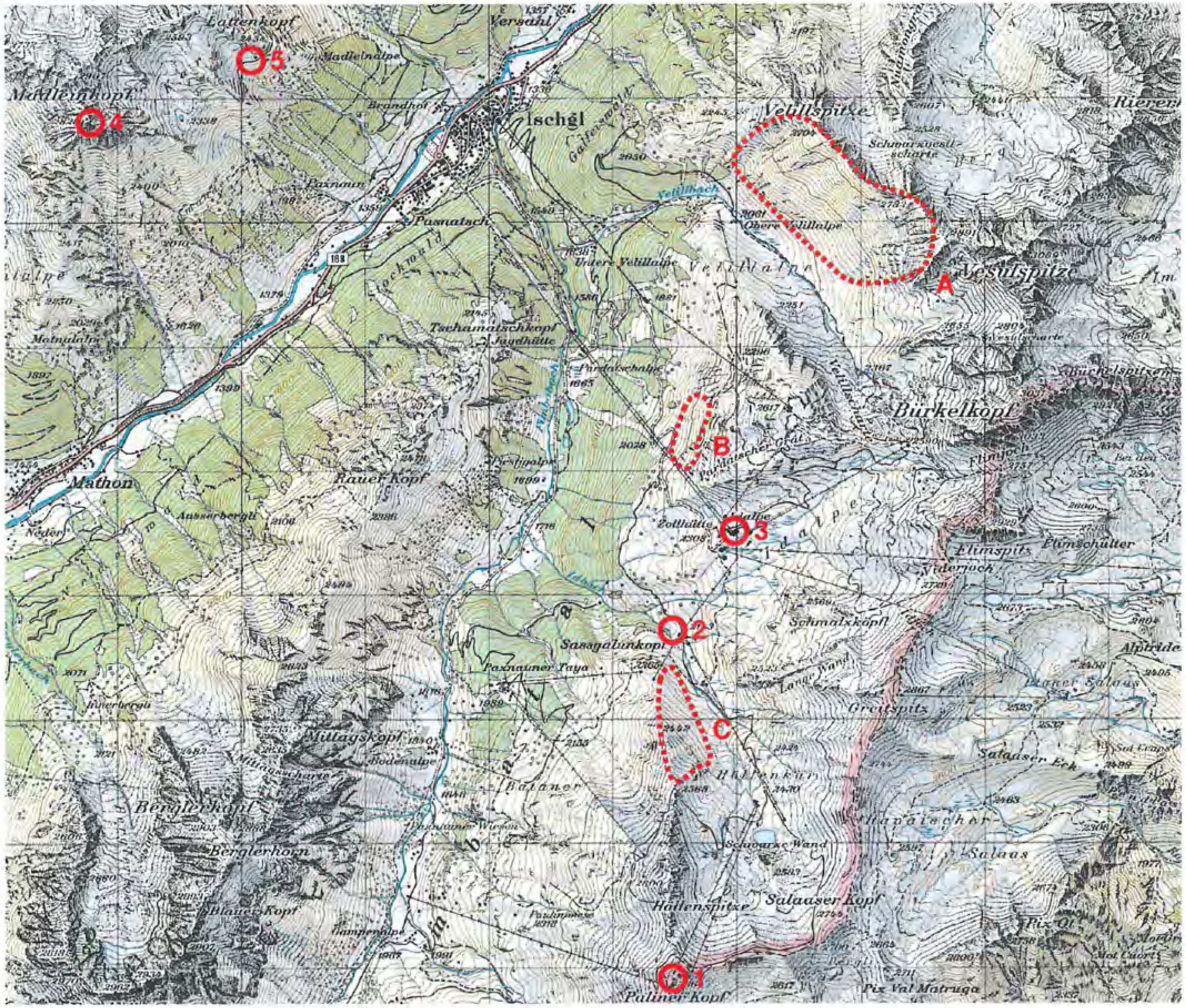


Figure C.40: Topographical map of the investigated release zones and weather stations

Release zones

A Velill

B Maas

C Höllkar

Weather stations

1 Palinkopf

2 Höllboden

3 Idalpe

4 Madlein

5 Pischgraben

Source: Bundesamt für Landestopografie - www.swisstopo.admin.ch

Schweizerische Eidgenossenschaft
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