MONITORING GLIDE AVALANCHES USING TIME-LAPSE PHOTOGRAPHY

MASTER THESIS

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Fribourg, the 1st of March 2014
ABSTRACT

During the winter 2011-2012, the Swiss Alps experienced a high glide snow activity. Glide cracks and glide avalanches presented a great concern for avalanche safety programs as they are difficult to forecast. Furthermore, glide cracks are difficult to control with explosives. A clear relationship between meteorological parameters, terrain characteristics and snow cover evolution could not be established to explain glide snow activity. It’s believed that presence of free water at the snow-soil interface could best explain fluctuations in glide velocities. As snow gliding activity is strongly related to glide avalanche release, it was suggested that glide rates monitoring could help forecasting glide avalanche triggering. Based on these assumptions, periods of glide crack activity were compared with meteorological and snow cover variables, with the goal to improve our understanding of snow gliding processes.

Since the winter 2008-2009, glide snow activity is monitored at two sites near Davos, Easter Swiss Alps, using time-lapse photography. Previous studies relied on a method based on dark pixel count to quantify the expansion of glide cracks over time. This method was evaluated and improved in order to obtain glide cracks values from the images. Periods of snow gliding activity and interesting glide cracks were identified in the time-lapse data base. 18 glide avalanches and 26 glide cracks were selected and analyzed. Numerical snow cover simulations were performed using the SNOWPACK model to link glide crack expansion with meteorological and snow cover variables.

Results showed that no clear diurnal variation of glide snow avalanche could be identified during winter time, when the snow cover is cold and dry. During spring time, when the snow cover is wet and warm, most glide snow avalanches occurred at noon. Observed time lag between the glide crack formation and the glide snow avalanche was larger during wintertime than during springtime. Cracks that did not result in an avalanche showed linear opening rates and cracks resulting in avalanches showed periods of stagnation in glide rates before the avalanche release. Most relevant weather parameters for the analysis of glide rates were snow surface temperature, air temperature and 3 days sum of new snow. Most relevant snow cover parameters were liquid water content and internal energy. Results revealed that snow gliding seems to be mostly driven by high liquid water content, positive air temperature and snow surface temperature close to zero degrees. If these parameters recover normal values, the glide process usually doesn’t develop into an avalanche.

Results may be specific to the investigated area, but especially the analysis of meteorological and snowpack variables combined with high temporal resolution glide rates shows promising outlook in developing practical forecasting tools.
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1. **INTRODUCTION**

1.1. **MOTIVATION**

The winter 2011-2012 was characterized by heavy snow falls and above average snow depths. The precipitations were especially intense during December and January, which resulted in record snow depths in some areas. The heavy snow fall in December covered the ground which was still warm. High snow gliding and glide avalanche activity were observed. Glide avalanches were larger and more frequent than usual. Periods of activity for glide-snow avalanches extended from December to March. The observed snow gliding activity during the winter 2011-2012 corresponded to a 30-year event (Figure 1.1) (Pielmeier et al., 2012).

![Figure 1.1: Glide crack observed in a snow cover which was several meters thick (Muotathal, SZ). Photo: S.Bürjeler, SLF.](image)

A lot of damage was caused by these avalanches. Around a fifth of the identified damages to people or buildings were induced by glide avalanches. The gliding of the snow cover as well as glide avalanches caused damages to lifts, buildings, roads, forest and agricultural land. Two persons died in a glide avalanche (Pielmeier et al., 2012).

Guaranteeing security at roads and ski resorts was problematic and presented a great concern for avalanche safety programs as glide avalanche are difficult to forecast. Furthermore, glide cracks, full-depth tensile fractures appearing when glide rates vary on a slope, are difficult to control using conventional explosive control measures (Clarke and McClung, 1999; Jones, 2004).
Until now, glide cracks and glide avalanches received little attention compared to other avalanches, such as skier-triggered dry snow slab avalanches. Physical processes relating to the triggering of glide avalanche are largely unknown. A clear link between snow gliding activity, terrain characteristics, meteorological variables and snow cover variables could not be yet identified.

1.2. GENERAL DESCRIPTION OF THE TOPIC

Snow gliding is the process in which the entire snow cover slowly moves downslope in the direction of the fall line (In der Gand and Zupančič, 1966). This occurs due to reduced friction at the snow-ground interface. When glide rates vary throughout a slope, a full-depth tensile fracture, called a glide crack, can form upslope of the area with higher glide rates, where tensile stresses concentrate (Clarke and McClung, 1999; Jones, 2004; Reardon and Fagre, 2006). Glide cracks often precede glide-snow avalanches, which occur when the entire snowpack glides over the ground until an avalanche release (van Herwijnen and Simenhois, 2012).

Glide avalanches are difficult to forecast and can be very destructive, as large volumes of snow are involved. These avalanches present a great concern for avalanche safety programs at, for instance, ski resorts, roads or towns. Furthermore, glide cracks are difficult to control using conventional explosive control measures (Clarke and McClung, 1999; Jones, 2004). Snow glide rates are related to glide avalanche release and it was suggested that glide avalanche release may best correlate with periods of rapid increases in glide rates (In der Gand and Zupančič, 1966; Clarke and McClung, 1999; Stimberis and Rubin, 2009; van Herwijnen and Simenhois, 2012).

Since the winter of 2008-2009, researchers at the WSL Institute of Snow and Avalanche Research SLF have been using time-lapse photography to monitor snow glide rates in the Eastern Swiss Alps, near Davos. Two time-lapse cameras are used to monitor field sites where glide cracks and glide avalanches are regularly observed. To monitor the expansion of glide cracks over time, a method has been used based on counting dark pixel. When a glide crack appears, the ground below the snow cover is exposed. Since the ground is much darker than snow, it can be identified on the time-lapse images and the number of dark pixels directly relates to the size of the glide crack (van Herwijnen and Simenhois, 2012).

Previous studies revealed that the presence of liquid water at the snow-soil interface is the most critical parameter in determining gliding behavior of the snow cover (Clarke and McClung, 1999; Zupančič, 1966; Mcclung and Clarke 1987). It is generally believed that the presence of water reduces the friction at the snow-soil interface and changes the viscosity of the snow cover. Changes in friction and viscosity are thought to explain fluctuations in glide velocities (McClung and Clarke 1987).

Developed by the WSL Institute of Snow and Avalanche Research SLF, SNOWPACK is a model which simulates the evolution of the snow cover based on meteorological input data. Physical processes such as heat transfer or water transport are modeled. As liquid water content likely influences glide rates, modeling the snow cover throughout the winter could help to better understand the physical processes related with increasing glide activity (SLF, 2012).
1.3. MAIN RESEARCH QUESTION AND GOALS

The research objectives for this master project are to improve our understanding of snow gliding processes with the long term goal to improve the forecasting of glide-snow avalanches. This is done by investigating glide rates in relation to meteorological characteristics. The main goal is to identify meteorological conditions associated with increased gliding rates, a prerequisite for glide avalanche release following glide crack opening. The research encompassed three steps:

1. Identify periods of increased gliding activity and interesting glide cracks in time-lapse database;

2. Evaluate and improve an image processing workflow to obtain glide crack expansion from the images;

3. Perform numerical simulations with SNOWPACK to link glide crack expansion with meteorological and snow cover variables.
2. RESEARCH QUESTION

The aim of this project was to identify meteorological parameters associated with periods of glide crack activity, with the goal to improve our understanding of snow gliding processes. More specifically, this project aimed to answer three main research questions:

1. Can time-lapse photography be used to monitor and measure snow gliding rates?

2. Do modeled snow cover variables from point measurements provide valuable information for forecasting multiple avalanche release zones?

3. What are the driving meteorological and snow cover parameters related to snow gliding activity?

The analysis therefore focused on three important points linked with the three poles previously cited: image analysis for glide rate monitoring; modeling the evolution of the snow cover at the field sites using SNOWPACK and establishing a link between glide rates and meteorological and snow cover variables.

1. With time-lapse photography, several glide cracks and resulting full-depth avalanches were monitored. Using an image analysis work flow, opening rates of the glide cracks were measured and full-depth avalanches were analyzed. Using a georeferencing method, the time-lapse images were scaled to estimate acceleration rates of glide crack opening.

2. Free water at the snow-soil interface highly influences snow gliding rates and thus full-depth avalanche release. Sources for free water input are known to be snowmelt, rain-on-snow events, melting of the base of the snow cover or water input from the ground due to capillary forces (Clarke and McClung, 1999; Mitterer and Schweizer, 2012). With this in mind, a link between snow gliding rates and changes of the snow cover was investigated. The focus of the analysis was on changes in the energy balance as well as on the evolution of the liquid water content of the snow cover. Meteorological data were used to model the physical processes occurring inside the snow cover with the SNOWPACK model.

3. Previous work identified lag times of 12-24 hours between increases in air temperature and snow gliding activity (Clarke and McClung, 1999). Existence of similar links was investigated. High temporal resolution data both for the images and the weather data allowed a more detailed analysis than previous studies.
3. BACKGROUND

3.1. SNOW GLIDING PROCESS – DEFINITION AND CHARACTERISTICS

On a slope, overall three deformation processes affect the snow cover (Figure 3.1). Settlement, which is perpendicular to the ground surface; internal shear deformation, which is parallel to the snow surface; and glide. Settlement and internal shear deformation result in creep. Glide is the process whereby a snow cover moves downslope along the snow-ground interface (Jones, 2004).

![COMPONENTS OF SNOWPACK DEFORMATION](http://www.geology.cwu.edu)

Four basics prerequisites must be met for snow gliding to occur (Clarke and McClung, 1999; In der Gand and Zupančič, 1966):

1. A smooth snow-soil interface with little roughness
2. A slope angle steeper than 15°
3. A temperature at the snow/ground interface at 0° Celsius, allowing for the presence of free water at the interface
4. A fairly uniform and cohesive snow cover without any prominent weak layer

The fastest glide rates are observed on areas with smooth snow-ground interface, such as polished rock slabs or grassy slopes (McClung and Clarke, 1999). Land with reduced agricultural use show higher glide rates than pastures (Newesely et al., 2000). Surfaces with high roughness (e.g. a harvested forest area, trees or rocks) work as obstacles and stabilize the snow cover so that glide is typically not observed.
Based on field observations, it was determined that the slope angle must be at least 15° for snow gliding to occur (Jones, 2004). Above this slope angle, the relationship between frictional forces and gravitational forces change. The downslope portion of the gravitational force acting on the snow cover can sometimes overcome the combined frictional forces from the snow-ground interface and the internal frictional forces within the snow cover (Jones, 2004). For different types of ground the slope angle can vary greatly, as the frictional forces might be very different on grass slopes, for little bushes or on smooth rock faces.

Previous studies revealed that the presence of liquid water at the snow-soil interface is of importance for the gliding behavior of the snow cover (Clark and McClung, 1999; In der Gand and Zupančič, 1966; McClung and Clarke, 1987). It was suggested that liquid water at the base of the snow cover changes the friction conditions at the snow-soil interface and changes in viscosity of the snow cover. These two variables are therefore believed to relate to fluctuations in glide velocities (McClung and Clarke, 1987). There are three different processes which can lead to the presence of free water at the snow-soil interface (McClung and Clarke, 1987): 1) water can percolate through the snow cover as the result of surface melting or rain on snow, 2) snow at the base of the snow cover can melt due to the release of heat from the ground, and 3) water can be produced at terrain features with strong energy release (e.g. bare rocks) or water originating from ground water outflow. Recently, a fourth process has been suggested, namely that moisture stored in the ground could be sucked up into the snow cover by capillary forces (Mitterer and Schweizer, 2012).

The presence of liquid water reduces friction at the snow-soil interface, affecting the gliding behavior of the snow cover (McClung and Clarke, 1987). Preliminary results of shear measurements on different substrates showed that the relation of shear strength to liquid water content behaves highly non-linear, but generally decreases with increasing water content (Mitterer and Schweizer, 2012).

Second, the liquid water content influences the viscosity of the snow cover, again impacting gliding rates. Izumi and Akitaya (1985) reported that snow hardness decreases significantly with increasing water content. Clarke and Mcclung (1987) developed a mechanical model relating the basal shear stress $\sigma_b$ to the glide velocity $U_0$:

$$\sigma_b = \frac{\mu U_0}{2(1-\nu)D^*}$$  \hspace{1cm} (3.1)

where $D^*$ is the stagnation depth, $\mu$ is the shear viscosity and $\nu$ is the viscous Poisson ratio of the snow above the snow-soil interface. $D^*$ is a geometrical parameter that is a function of the ground geometry and the water distribution at the interface. $\mu$ and $\nu$ are functions of the snow cover density and of the liquid water content of the snow cover. Increasing the liquid water content at the snow-soil interface reduces the shear viscosity and thus increases the glide rate.
3.2. GLIDE CRACK – DEFINITION, FORMATION AND EVOLUTION

When glide rates vary on a slope, a full-depth tensile fracture, called glide crack, forms upslope of the area with higher glide rates where stress is concentrated (Figure 3.2) (Clarke and McClung, 1999; Jones, 2004; Reardon and Fagre, 2006). This crack initiates at the snow-ground interface and propagates upwards toward the snow surface, perpendicular to the interface (McClung, 1987). As the opening of a tensile crack causes a redistribution of the internal forces within the snow cover, forces are transferred from the crown to a compression zone at the down-slope end of the snow slab. The sliding slab is then held in place by a snow cover zone called the stauchwall. The stauchwall is the bottom, or downhill, edge of a slab avalanche's crown area. The gliding snow cover upslope the stauchwall might present undulations and folds, indicating that the whole slab is gliding considerably (Bartelt et al., 2012).

Glide crack formation is highly dependent on the ground topography, ground roughness and slope angle. Typical terrain configurations for glide crack formation are convex rolls where tensile stresses are concentrated; slopes where the ground roughness changes; and below steps in smooth rock faces (McClung and Schaerer, 1993; Lackinger, 1987; McClung 1987). It was suggested that a slope angle of minimum 30° is required for glide crack formation for area with little surface roughness such as grass covered slopes or rock slabs. Areas with higher ground surface roughness may require a steeper slope angle (In der Gand and Zupančič, 1966; McClung 1987).

It is known that glide cracks are often associated with glide avalanche. Field observations show that glide crack formation precede full-depth glide avalanches, but that glide avalanche release does not always immediately follow glide crack formation (Clarke and McClung, 1999; Feick et al., 2012). Feick et al. (2012) also showed that 50% of the glide avalanche he observed released without an observable glide crack opening. His study was based on time-lapse photography with a 15 minutes interval.

Figure 3.2: Glide crack at the Dorfberg site, Davos, GR. Photo R. Meister- SLF.
3.3. SNOW-GLIDING AVALANCHE – DEFINITION AND CHARACTERISTICS

Glide avalanches occur when the entire snow cover glides over the ground until an avalanche release (Figure 3.3). Snow glide rates are related to glide avalanche release and it was suggested that glide avalanche release may best correlate with periods of rapid increases in glide rates (In der Gand and Zupančič, 1966; Clarke and McClung, 1999; Stimberis and Rubin, 2009; Van Herwijnen and Simenhois, 2012). Full-depth avalanches are also commonly associated with wet, seasonal snow covers (Clarke and McClung, 1999).

Figure 3.3: Glide avalanche which released at Frauenkirch, near Davos, December 2011. Photo: S. Margreth, SLF.

3.3.1. Evolution from a glide crack to a glide avalanche

Feick et al. (2012) monitored two different slopes with well known gliding-snow events during one winter. Their results showed that about every tenth full-depth avalanche occurred directly above and not below a glide crack, as was already mentioned by Lackinger (1987).

Feick et al. (2012) also underlined that the majority of glide cracks never develop into an avalanche. Only about 40% of the glide cracks resulted in an avalanche. Their results also showed that 15% of glide cracks resulted in avalanche release within the first hour and 40% within the first 5 hours after the crack opened. As mentioned by Clarke and McClung (1999), Feick et al. (2012) observed that in many cases glide avalanches frequently occurred without a previous glide crack. On the two monitored slopes Feick et al. (2012) observed during their study, for 41% and 55% respectively of the glide avalanche no glide-crack opening could be identified on the previous photo. This might be due to the large distance between the camera and the studied slope, the flat angle of incidence between the camera and the slope and the time interval of 15 minutes between each photo. Results also showed that short time lags between initial crack opening and full-depth avalanche releasing were typical.
3.3.2. Seasonal and diurnal variations

Glide activity is mainly observed either in early winter or in spring (Clarke and McClung, 1999; McClung et al., 1994). Considering the meteorological conditions, Clarke and McClung (1999) distinguished between cold and warm temperature events. Cold temperature events are defined as full-depth avalanches that occur when air temperature is below freezing and there has not been any form of liquid precipitation. These events are the most difficult to predict (Clarke and McClung, 1999). Warm temperature events are defined as glide avalanches triggered by snowmelt generated by warm periods (air temperature > 0°C). As these two kinds of events do not present the same characteristics, it is assumed that different mechanisms might trigger the glide activity during early winter or spring (Clarke and McClung, 1999; Dreier, 2013).

The existence of diurnal variations is unclear. Lackinger (1987) observed most avalanche releases in the evening or at night. McClung et al. (1994) examined two years of glide activity in British Colombia and found increased avalanche activity during the day in the first year, but no clear diurnal variation during the second year. Clarke and McClung (1999) detected no significant differences in glide activity between day and night for the same study site. On the other hand, Feick et al. (2012) observed a clear diurnal cycle with most events occurring at noon for spring avalanches. These differences might be due to the climatic conditions of each study site, the particularity of each winter, and the particularity of each study site (elevation, slope angle, aspect).

3.3.3. Meteorological drivers

Three meteorological trigger mechanisms are known to affect full-depth glide avalanches release: 1) loading by new snow, 2) rain-on-snow events and 3) snowmelt (Clarke and McClung, 1999). Snowmelt can either occur due to incoming solar short wave radiation, or by warming air temperatures (Clarke and McClung, 1999).

Lackinger (1987) investigated 21 avalanches and reported more glide avalanches after several days of high air temperature than after periods of rain. Glide avalanche release due to loading by fresh snow was only observed in one case during a period of heavy snowfall. Clarke and McClung (1999) investigated 104 avalanches and reported more glide avalanches after rain-on-snow events or periods of snowmelt. The seemingly contradictory results can be attributed to climatic differences between the continental Swiss Alps (Lackinger, 1987) and the maritime Canadian Cascade mountain ranges (Clarke and McClung, 1999). Furthermore, differences in classification are also responsible for these differences, since Lackinger (1987) observed rain-on-snow events during periods of melting, and interpreted the snowmelt as being the more critical trigger mechanism (Jones, 2004).

Both Lackinger (1987) and Clarke and McClung (1999) also observed glide avalanches releases on days with cold temperature. Clarke and McClung (1999) explain this phenomenon by the presence of free water at the snow-soil interface that is unaffected by cold air temperature, since the snow cover acts as an insulator.

Another explanation was provided by McClung and Schäerer (1993). They hypothesize that diurnal changes in snow surface temperature influences the tensile stress in the crown area of a glide zone.
Cooling of the air temperature cause the snow to contract as it freezes, resulting in fracture formation and avalanche release. This hypothesis was not verified by any measurements.

Peitsch et al. (2012) analyzed 55 wet slab and 182 glide avalanches along the Going-to-the-Sun Road corridor, Montana, USA, and reported that air temperature and snow cover settlement appeared to be the most important variables in glide crack and glide avalanche occurrence. They suggested that free water moving through the snow cover and the interaction of water with snow layers or ground interface presumably triggered glide cracks and glide avalanches.

Dreier (2012) found that the most important weather parameters for triggering glide avalanches in winter were maximum air temperature, 5-days sum of fresh snow and incoming shortwave radiation. Snow surface temperature, minimum air temperature, difference in air temperature to the day before and relative humidity were identified to be the most important variables for triggering glide avalanches in spring.

3.3.4. Terrain characteristics of snow-gliding avalanches

Glide snow avalanches are mostly observed on steep, i.e. 30° to 40° slopes (Leitinger et al., 2008; Newesely et al., 2000) with a smooth snow-soil interface such as smooth rock (Stimberis and Rubin, 2011), grass (In der Gand and Zupančič, 1966) or tipped-over bamboo bushes (Endo, 1984) (Figure 3.4). Most full-depth avalanches release on convex rolls (In der Gand and Zupančič, 1966; Dreier, 2012). Dreier (2012) also suggested that the avalanche starting zone and the area below were steeper than the area above the starting zone and that the avalanche starting zones were steeper than the remaining areas of a slope. Lackinger (1987) suggested that glide cracks often develop at similar slope positions, but that they only develop into glide avalanches in specific starting zones.

Figure 3.4: Gliding snow on a smooth grass slope, Schonegg, BE. Photo: R. Laan, SLF.
3.4. OBSERVATION TECHNIQUES OF GLIDE RATES AND FORECASTING OF SNOW-GLIDING AVALANCHES

Different methods were developed to measure the snow glide rates to forecast glide-snow avalanches.

First measurements of glide rates were performed by In der Gand and Zupančič (1966) using glide shoes (Figure 3.5). Glide shoes are rectangular plates of aluminum with inner baffle, placed on the ground before snowfall. The glide shoe is connected to a potentiometer with a cord in order to record the downward motion of the snow cover. Glide shoes provide accurate point measurements of glide rates and are still used for research today (Leitinger et al., 2008; Barbero et al., 2011).

Akitaya (1980) used video tape recorder to monitor glide cracks and glide avalanches. During seven years eight avalanches were monitored. He observed three different types of avalanche release. The first type was characterized by undulations in the snow cover below the glide crack. A fracture in a fold in the compression zone then triggered the release of the snow slab. The second type was characterized by folds on the snow cover, without any fracture pattern prior to avalanche release. Glide avalanches occurred with the formation of new tensile cracks. Finally, the third type was characterized by a sudden release of the slab without any warning.

Lackinger (1987) measured glide velocities on the expanding glide crack and measured micro-seismic and acoustic emissions in the area of the glide crack. Results showed that an increase in amplitude and frequency of seismic signal occurred 3 hours before the release of a full-depth avalanche.
Lackinger (1987) attributed the increase in seismic activity with the formation of micro-fractures in the snow as well as an increase in gliding rates.

Rice et al. (1996) developed a method involving the use of creep and glide sensors. These sensors are poly vinyl chloride (PVC) pipes of one meter length, instrumented with an accelerometer and a temperature sensor. Three sensors were placed at different heights from the surface. The first sensor was placed at the ground, the second sensor was placed one meter above the ground and the third sensor was placed two meters above the ground. These sensors allowed the measurement of the elastic response of the snow cover to explosives and the increase in creep rates due to loading that preceded widespread avalanching. Results showed that this method was suitable for measuring creep rates but limited for measuring glide rates.

Wilson et al. (1996) developed a similar method using sprung probes including an accelerometer and a temperature sensor. These probes were used to monitor the tilt angle on the glide slope. The probes were mounted in the ground surface of the avalanche starting zone. Results showed that the probes could monitor snow movement prior to avalanche release with some reliability. However, some limitations exist: avalanche releases are needed so that the probes can return to their upright position. Furthermore, this method does not distinguish between snow gliding and creep movement. Finally, this system does not distinguish glide-snow avalanches from dry slab avalanches.

Clarke and McClung (1999) focused on meteorological variables to forecast avalanche activity. Their results showed that glides rates were linked with increased air temperatures with lag times of 12-24 hours for warm temperature events. However, relationship between air temperature and gliding activity is complex, as several processes related to glide are indirectly influenced. Furthermore, observations showed that glide avalanche might release during periods of freezing temperatures.

Satellite images were used by Feick et al. (2012) to monitor glide crack opening and glide avalanche release. They developed a method allowing the automatic detection and mapping of glide cracks. Results showed that this method was suitable for automatic detection of glide cracks. Some limitation exists in terms of over-estimating glide areas due to the presence of rocks, trees or other structures, or in steep snow-free areas. Images from temporal high resolution time-lapse photography were also used to monitor glide-crack activity and glide-avalanche release. Analysis of these images showed clear diurnal and seasonal cycles, and several patterns of glide avalanches could be observed.

Hendrikkx et al. (2012) used time-lapse photography to monitor glide crack and glide-snow avalanches. Observations were linked to meteorological variables. Several correlations were found between a number of meteorological variables and periods of glide and non-glide activity. These variables were air temperature, relative humidity, air pressure, incoming and reflected long wave radiation, snow water equivalent, total precipitation, and snow depth. However, some limitations in the interpretation of these results exist as this analysis was based on only three events and on a small sample of 50 hours of meteorological variables.

Van Herwijnen and Simenhois (2012) used time-lapse photography to monitor glide rates and glide-snow avalanche release. Their method is based on dark pixel count to monitor the expansion of glide cracks over time. On an image, the white pixels correspond to the snow and the dark pixels correspond to the ground exposed when a glide crack appears. Results showed an increase in glide
rates several hours prior to avalanche release. However, this method presents limitations as it cannot be used at night or during conditions with bad visibility.

A method allowing the measurement of glide rates and glide acceleration combined with the monitoring of meteorological condition might be the most suitable for glide-snow avalanche forecasting. Especially meteorological variables that produce free water at the snow-soil interface might be of great importance. These include precipitation (mostly rain), air temperature and solar radiation (Jones, 2004).
3.5. CONTROL OF SNOW-GLIDING AVALANCHES

Glide snow avalanches are notoriously difficult to control as they are not usually triggered by increasing loads. Thus, controlling glide-snow avalanches using explosive along the glide crack are generally unsuccessful (Jones, 2004). Tests were done using explosives along the stauchwall. They showed encouraging results for controlling avalanches in ski resorts (S. Anthamatten, personal communication).

Since free water at the snow/ground interface reduces basal friction and the shear viscosity of the snow cover (Clarke and McClung, 1999), it has been suggested that adding water into the avalanche start zone could trigger the avalanche. Water could be introduced from the air (e.g. helicopter water bombing), by pumping water into the start zone, or by using heat tape or other heat conductors at the snow/ground interface to generate free water (Jones, 2004). However, adding water into the glide crack by helicopter showed very limited results (S. Anthamatten, personal communication).

Other methods were proposed to stop the glide movement of the snow. As glide avalanche often appear each year in the same location, it has been suggested to increase the ground friction in areas where snow gliding activity is observed. This can be done by fixing tree trunks parallel to the ground or by anchoring tripods into the ground during summer time. These installations showed promising results in different ski resorts (P.-V. Amaudruz; P. Fardel, personal communications).

Snow groomers are also efficiently used to control snow-glide areas by taking away the snow from the avalanche zone (Figure 3.6) (V. Bettler, personal communication).

Unfortunately, little information about these methods exists in the literature.

Figure 3.6 : Snow groomer at work in the ski resort of Montana, aiming to stabilize the glide crack, February 2012. Photo V. Bettler, security service of Crans-Montana.
4. STUDY SITES

The Dorfberg site and the Wannengrat site are located above the town of Davos, Graubünden, Switzerland (Figure 4.1). The Dorfberg site is located under the Weissfluhjoch, where the WSL Institute for Snow and Avalanche Research SLF conducts regular observations since 1936. The Dorfberg site itself has also a long history of glide avalanche research. In der Gand and Zupančič (1966) already studied glide cracks and glide avalanches on this slope in the sixties. Gliding snow avalanche studies on the Wannengrat site are conducted since the winter 2009.

Figure 4.1: General presentation of the different study sites. The Wannengrat site is delimited in red and the Dorfberg study site is delimited in blue (Swisstopo, 2012).
4.1. THE DORFBERG SITE

4.1.1. Description and localization

Dorfberg is a large ESE facing slope ranging from around 1700m to around 2300m (Figure 4.2). The mean slope angle is 28° and small rock faces are present on the slope. The study site is dominated by the Salezer Horn, a small mountain reaching 2536m, and is located below the study site of Weissfluhjoch (approximately 2540m). Avalanche barriers are present in the upper part of the slope, facing SE and ranging from an elevation of 2460m to 2260m. A cable car, on the west side of the slope, provides an easy access to the study site (Figure 4.3).

Vegetation at the Dorfberg consists of small patches of dense forest, shrub and steep meadows. The bedrock is composed of fine-grained Gneiss and mica schist’s. Soil is mainly brown podzol (Bosshard, 1986). Mean annual temperature for the Weissfluhjoch (780615/189636) is -1.9°C according to the 1981-2010 norm. Mean annual temperature for Davos (783514/187457) is 3.5°C according to the 1981-2010 norms (MeteoSwiss, 2013). Appendix 1 presents the climatic ranges of Davos and the Weissfluhjoch for the 1981-2010 periods.

Figure 4.2: Monitored slopes at the Dorfberg site, autumn and winter. Photos are provided from the time-lapse cameras.
Figure 4.3: Overview of the Dorfberg study site. The red star shows the location of the meteorological station. The red circle shows the location of the WSL Institute for snow and avalanche research SLF building, where a meteorological station and the time-lapse camera are located (Swisstopo, 2012).
4.1.2. Measurement instruments and methods

A camera (6 Mpixel Nikon Koolpix 4300) was installed in the fall of 2008 at the SLF in Davos monitoring large parts of the Dorfberg. It is connected to a desktop computer and images were stored every 15 minutes. Since the winter 2012-2013 images are stored every 2 minutes. The monitored area ranges from 1700m to 2400m. The standard camera is recording pictures in the visible light spectrum range, meaning that there is no data during the night or during bad weather conditions. The camera position towards the slope is oblique (van Herwijnen and Simenhois, 2012; Feick et al., 2012).

On the Dorfberg slope, on a small flat area at 2410m, a weather station records the following parameters: date; relative humidity; surface temperature; air temperature; incoming shortwave radiation; outgoing shortwave radiation; wind speed; wind direction; snow height. A first data logger called Dorfberg 1 (DFB1) is in use since February 2009 and records data every 30 minutes and a second data logger called Dorfberg 2 (DFB2) is in use since February 2010 and records data every 10 minutes.

Three other stations are located in the immediate vicinity of the Dorfberg site: the Weissfluhjoch weather station, the SLF weather station and the weather station of Klosters-Madrisa (Figure 4.4).

![Figure 4.4: Location of the different weather stations used to complete the missing values of the Dorfberg dataset. The Klosters-Madrisa weather station is in black, the Weissfluhjoch weather station is in yellow and the WLS Institute for snow and avalanche research SLF weather station is in blue. The red star represents the Dorfberg weather station (Swisstopo, 2012).](image-url)
4.2. THE WANNENGRAT SITE

4.2.1. Description and localization

The Wannengrat site study is a large NE to SE slope ranging from around 2460m to 2636m (Figure 4.5). The main peak dominating the slope is Strela (778921/186890), reaching 2636m. The slope forms a bowl and is surrounded by a crest ranging between 2490m and 2636m. The mean slope angle is of 35°, and small rock faces are present on the slope. A ski area on the east side of the slope provides an easy access to the study site.

The bedrock is composed of fine-grained Gneiss and mica schist’s. Soil is mainly brown podzol (Bosshard, 1986). Vegetation at the Wannengrat is composed of steep mountain meadows. The slope also presents some rocky parts and some eroded soil parts.

![Figure 4.5: Monitored slopes at the Wannengrat site, autumn and winter. Photos are provided from the time-lapse cameras.](image)

4.2.2. Measurements instruments and methods

A camera (7 Mpixel Canon PowerShot) was installed in the fall of 2009 at the Wannengrat study site. It is connected to an automatic weather station at the top of a ridge at 2492m. Images were stored every 5 minutes and were manually retrieved approximately every 10 days. The monitored area ranges from 2480m to 2600m.

Several automatic meteorological stations are located in the immediate vicinity. Three of these stations are relevant for this study: The Wannengrat 5 (WAN5) station, the Wannengrat 6 (WAN6) station, where the camera is fixed, and the Wannengrat 7 (WAN7) station (Figure 4.6). These stations record different variables.

The WAN5 station is located downslope, on the west side of the NW-SE Strela ridge, at an altitude of around 2420m. The following data are recorded every 10 minutes: date; relative humidity; surface...
temperature; air temperature; incoming shortwave radiation; outgoing shortwave radiation; incoming long wave radiation; outgoing long wave radiation; wind speed; wind direction; snow height. The WAN6 station is situated on the NW-SE Strela ridge, at an elevation of 2492m. The following data are recorded every 10 minutes: date; relative humidity; air temperature; wind speed; wind direction; snow height. The WAN7 station is located on a small hill at around 2440m. The following data are recorded every 10 minutes: date; relative humidity; surface temperature; air temperature; incoming shortwave radiation; outgoing shortwave radiation; incoming long wave radiation; outgoing long wave radiation; wind speed; wind direction; snow height. To obtain consistent time series, data from the WAN7 weather station were mainly used, as the recorded data presented the most consistent time series. To fill up gaps in the data, the two other stations were used.

Figure 4.6: Overview of the Wannengrat study site. The red star represents the Wannengrat 6 meteorological station located on the ridge. The blue star represents the Wannengrat 5 weather station and the yellow star represents the Wannengrat 5 weather station. The time-lapse camera is located at the Wannengrat 6 weather station (red star) (Swisstopo, 2012).
5. METHODOLOGY

This next section will present the methods used to complete the meteorological time series, the SNOWPACK model and the method used to obtain glide rates from the time-lapse images.

5.1. METEOROLOGICAL DATA – COMPLETION AND HOMOGENIZATION

5.1.1. Linear regression and correlation rate

To fill gaps in the weather data of the Dorfberg (DFB1) and Wannengrat 7 (WAN7) weather stations, linear regression were used. First, the linear dependency between the study sites and the surrounding stations was investigated. For DFB1, Weissfluhjoch (WFJ), Klosters-Madrisa (KLO) and Davos-SLF (SLF) were considered. For WAN7, Wannengrat 6 (WAN6) and Wannengrat 5 (WANS) were considered. 80% of the available valid data were used to calculate the correlation coefficient for each parameter between the study site station and a surrounding station (Figure 5.1). The surrounding weather station with the highest correlation was used for completing missing data using a linear fit.

![Graph showing linear regression for air temperature measurements between the Dorfberg and Weissfluhjoch meteorological stations for the 80% of valid data from winter 2011-2012. The regression function (equation $y = 0.94x - 2.9$) is used to complete missing values of the Dorfberg station.](image)

Figure 5.1: Linear regression for air temperature measurements between the Dorfberg meteorological station and the Weissfluhjoch meteorological station for the 80% of the valid data from the winter of 2011-2012. The regression function (equation $y=0.94x-2.9$) of the linear fit (red line) is then used to complete the missing values of the Dorfberg station.

Using the linear fit with the values form the corresponding weather station, a new dataset was created. The remaining 20% of the data that were not used to generate the regression function were then compared to the calculated values. If the difference between these two dataset did not exceed 5%, the new dataset was considered as acceptable. The missing values could then be replaced by the calculated values.
5.1.2. Parameterization of snow surface temperature values

There were gaps in the snow surface temperature measurements at the WAN7 weather station. Snow surface temperature was therefore estimated with the incoming long wave radiation measurements using the Stefan-Boltzmann law (Sedlar, Hock, 2008).

\[
L \uparrow = \varepsilon \sigma_{sb} \ T^4 + (1-\varepsilon) L \downarrow \quad \left[ \frac{W}{m^2} \right] \quad (5.1)
\]

\[
T_s = \sqrt{\frac{4 L \uparrow + (1-\varepsilon) L \downarrow}{\varepsilon \sigma_{sb}}} \quad [K] \quad (5.2)
\]

With \( T_s \) the snow surface temperature in [K], \( L \uparrow \) the outgoing long wave radiation in \( \left[ \frac{W}{m^2} \right] \), \( L \downarrow \) the incoming long wave radiation in \( \left[ \frac{W}{m^2} \right] \), \( \varepsilon \) the emissivity of snow set at 0.95 and \( \sigma_{sb} \) the Stefan-Boltzmann constant equal to \( 5.6704 \times 10^{-8} \left[ \frac{W}{m^2K^4} \right] \).

5.1.3. Replacement of snow values

There were offsets, anomalies and missing values in snow height measurements for the Dorfberg (DFB1) weather station. Snow height values were therefore replaced with values from the Klosters-Madrisa (KLO) weather station (Figure 5.2). This station is located at a similar elevation and is located at short distance from the Dorfberg site. Note that snow height is difficult to measure and the measurements at the weather station of Klosters-Madrisa are more reliable.

![Graph showing snow height values for Dorfberg and Klosters-Madrisa](image)

Figure 5.2: Presentation of the snow height values for the Dorfberg meteorological station (in red) and the Klosters-Madrisa meteorological station (in blue) for the winter season 2011-2012. The Dorfberg dataset present an offset of 60 cm in the beginning of the season. Gaps in the Dorfberg dataset are also visible.
5.1.4. Linear interpolation

5.1.4.1. Single missing values

Some single missing values could not be completed as the surrounding weather station also presented empty values. If isolated missing values were observed, they were completed by linear interpolation. The mean between the previous and the following value was calculated and the missing value was completed by this mean.

5.1.4.2. Air temperature values

The Dorfberg weather station is located at an elevation of 2140 meters, but snow gliding activity is mainly observed at around 1800m. As air temperature plays a major role in snow gliding activity, the air temperature measurements were linearly interpolated to obtain values that are representative for 1800m. To do this, a lapse rate \( \frac{\Delta T}{\Delta h} \) was calculated using air temperature measurements from DFB1 and SLF:

\[
\text{grad } T_a = \frac{T_{a,\text{DFB}} - T_{a,\text{SLF}}}{\Delta H} \quad [\degree C/\text{100m}] \quad (5.3)
\]

With \( T_{a,\text{DFB}} \) the air temperature at DFB, \( T_{a,\text{SLF}} \) the air temperature at SLF and \( \Delta H \) the difference in elevation between both stations. The air temperature at 1800m was then calculated as:

\[
T_{a,1800m} = T_{a,\text{DFB}} - \text{grad } T_a \cdot \Delta h \quad [\degree C] \quad (5.4)
\]

with \( \Delta h = 200 \text{m} \).

5.1.4.3. Interval homogenization

The weather stations collected data every 10, 15 and 30 minutes. To homogenize the data, an interval of 15 minutes was chosen, which correspond to the most satisfying compromise between high resolution and availability of the data. A homogeneous dataset was also required for the SNOWPACK model (see section 5.2). Linear interpolations were used to transform the interval into 15 minutes time steps. A function was created to homogenize the intervals of each dataset.
5.2. SNOWPACK – DESCRIPTION AND USE

5.2.1. Description of the SNOWPACK

SNOWPACK is a physically based energy balance model developed by the SLF to simulate the evolution of the snow cover based on meteorological input data (SLF, 2012).

SNOWPACK describes the evolution of the snow cover during winter and its interaction with the environment, focusing on a detailed description of the mass and energy exchange between the snow, the atmosphere and optionally the vegetation cover and the soil. The energy balance will include the solar radiation absorption, the sublimation/deposition of water vapor, the melting and refreezing of water as well as the heat conduction. SNOWPACK parameterizes snow microstructure and thus allows a detailed representation of the layered snow structure. Figure 5.3 illustrates the physical processes modeled by SNOWPACK. Following individual processes are modeled: heat transfer, settling, phase change, water transport and metamorphism (Figure 5.4) (SLF, 2012). Meteorological data is used as model input.

Figure 5.3: Illustration of the physical processes modeled by SNOWPACK (SNOWPACK Documentation, 2012).
Figure 5.4: Illustration of the structure of the SNOWPACK model and presentation of the modeled processes (SNOWPACK Documentation, 2012).
5.2.2. Practical running and using of SNOWPACK

To perform a simulation, three files provided in an ASCII file format are required: a SMET file, a SNO file and an INI file.

The SMET file contains a description of the localization of the weather station as well as the meteorological input data. The SNO file contains the description of the meteorological station and of the place where the snowpack has to be simulated. Several slope angles and slope orientations can be chosen, allowing simulations for various aspects at the same time. Up to nine aspects can be simulated at once (N – NE – E – SE – S – SW – W – NW – Flat). It’s also possible to simulate the snowpack for a chosen slope angle and slope orientation by entering the angles in degree in the *.sno file. By default, the model simulates the snowpack for a flat field. A soil model can also be provided, allowing the simulation of processes taking place at the snow-soil interface. Finally, the INI file contains the simulation configuration parameters. The *.ini file is created using the Inishell platform, a software allowing the creation of the configuration files.

In order to describe the processes occurring within the snow cover, SNOWPACK was used to model the snow cover for each winter and each study site. First, meteorological input and weather station information were provided to the SNOWPACK model. The description of the place where the snowpack had to be simulated was formatted. Then the model was tested using 30 minutes time step and calibrated. When the results were satisfying, a high resolution simulation with a 15 minutes interval was performed, providing the snow cover variables for each study site (see section 5.2.3). All simulations were run for the entire winter season, i.e. from the beginning of October until the end of April.
5.2.2.1. Model inputs

First SMET files were created for each station and each winter, providing meteorological data input and information about the location of the weather station.

The SMET file is composed of a header that contains a description of the location of the weather station and a field that contains the meteorological input data (Table 5.1 and table 5.2). For each field, a unit offset and a unit multiplier are defined. The unit offset is used for converting temperature values expressed in Celsius to Kelvin values. The unit multiplier is used to convert the relative humidity values expressed in percent in absolute values. Snow height values are also converted from centimeter to meter values.

<table>
<thead>
<tr>
<th>Header</th>
<th>Dorfberg</th>
<th>Wannengrat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station id</td>
<td>Dorf</td>
<td>Wan</td>
</tr>
<tr>
<td>Station name</td>
<td>Dorfberg</td>
<td>Wannengrat</td>
</tr>
<tr>
<td>Latitude</td>
<td>46.82058</td>
<td>46.80758</td>
</tr>
<tr>
<td>Longitude</td>
<td>9.82997</td>
<td>9.78797</td>
</tr>
<tr>
<td>Altitude</td>
<td>2140</td>
<td>2440</td>
</tr>
<tr>
<td>Nodata</td>
<td>-999</td>
<td>-999</td>
</tr>
<tr>
<td>Tz</td>
<td>+01</td>
<td>+01</td>
</tr>
</tbody>
</table>

Table 5.1: Presentation of the parameters contained in the header of a SMET file.
<table>
<thead>
<tr>
<th>Fields</th>
<th>Units offset</th>
<th>Units multipliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date (timestamp)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Snow surface temperature (TSS)</td>
<td>273.15</td>
<td>1</td>
</tr>
<tr>
<td>Air temperature (TA)</td>
<td>273.15</td>
<td>1</td>
</tr>
<tr>
<td>Relative humidity (RH)</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Incoming shortwave radiation (ISWR)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Outgoing shortwave radiation (OSWR)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Incoming longwave radiation (ILWR)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Outgoing longwave radiation (OLWR)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Wind speed (VW)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Wind direction (DW)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Snow height (HS)</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Precipitation rate (PSUM)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Snow ground temperature (TSG)</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.2 : Presentation of the fields containing the meteorological parameters used for the creation of a SMET file.

For each station and each winter, several *.sno files were created, describing various locations for the snowpack simulation: 1) a flat site, represented by a slope angle and a slope azimuth of 0°; and 2) slope simulation with a slope angle and a slope azimuth representative of the slope where glide avalanches were generally observed. For the Wannengrat site, the slope angle was set at 34° and the slope azimuth was set at 120°. For the Dorfberg site, the slope angle was set at 32° and the slope azimuth was set at 135°. The *.sno file describing the flat site served to calibrate the model.

The simulation configuration parameters were expressed in the *.ini file. The default settings were mainly used, but some parameters had to be adapted. Table 5.3 presents which parameters were modified for the simulations.

Concerning the snowpack settings, the snow height was used to calibrate the model (see chapter 5.2.2.2). Only Neumann boundary conditions were assumed.

As a soil layer was introduced in the *.sno file, it was then considered for the simulation. Water transport models for snow and soil were modeled using the Richard’s equation. For more details, see Wever et al., 2013.

Interpolations were also performed. The snow height measurements were linearly resampled using a mean average filter and the new snow was accumulated by aggregating all valid values.
<table>
<thead>
<tr>
<th>Modified parameters</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output settings</strong></td>
<td></td>
</tr>
<tr>
<td>Cumsum mass</td>
<td>If CUMSUM_MASS is set, current value of cumulated masses since begin of the run are dumped. Precipitations are always dumped as rates $[\text{kg m}^{-2} \text{ h}^{-1}]$. CUMSUM_MASS was set as false.</td>
</tr>
<tr>
<td>Precipitation rates</td>
<td>Write precipitation as rates $([\text{kg m}^{-2} \text{ h}^{-1}])$, default) or as sums over the output time step. There were set as false.</td>
</tr>
<tr>
<td><strong>Snowpack settings</strong></td>
<td></td>
</tr>
<tr>
<td>Enforce measured snow heights</td>
<td>Input mode by which a measurement of snow depth is used to drive the snow cover mass balance. Can be set to true or false. It was set as false.</td>
</tr>
<tr>
<td>Change boundary conditions (BC)</td>
<td>Use measured surface temperature as Dirichlet temperature boundary conditions (BC) for sub-freezing snowpack’s and switch to Neumann only for melting snowpack’s. If set to false, assumes Neumann boundary conditions. It was set as true.</td>
</tr>
<tr>
<td>SNP soil</td>
<td>Define if soil layers as defined by the *.sno files are included in the simulation or not. It was set as true.</td>
</tr>
<tr>
<td>Water transport model for snow</td>
<td>Define which water transport model to use in snow: simple bucket model, Nied model or Richard’s equation solver. Richard’s equation was chosen.</td>
</tr>
<tr>
<td>Water transport model for soil</td>
<td>Define which water transport model to use in soil: simple bucket model, Nied model or Richard’s equation solver. Richard’s equation was chosen.</td>
</tr>
</tbody>
</table>

Table 5.3: Presentation of the different parameters that were modified in the *.ini configuration file. For the other parameters the default values were used to run the simulations (Snowpack documentation, 2012).
5.2.2.2. Model calibration

For each station and each year, initially a flat field simulation was performed. This first simulation was computed using the measured snow height as input for the model. The resulting calculated precipitation rate at the surface was then used for a new meteorological input file for the second flat field simulation.

By accumulating the solid precipitation rate, the snow height was modeled and compared to the measurements (Figure 5.5). This provided information about the accuracy of the model settings. Several parameters had to be modified in the configuration file before obtaining a satisfying modeled snow height.

![Figure 5.5: Comparison of the modeled (blue line) and measured (red line) snow height at the Dorfberg field site for the 2011-2012 winter.](image)
5.2.2.3. **Soil layers**

Once the snow cover modeling provided satisfying results, a soil model was introduced. The soil model contains ground characteristics of the study sites and is included in the *.sno file. 30 layers were created. Based on preliminary testing, 30 layers provided the best results. Each soil layer had several variables (Table 5.4): heat capacity, density, conductivity, volumetric water content, volumetric void content, volumetric soil content, soil temperature, layer thickness, grain size and soil albedo. The soil temperature was set to 10°C, which corresponds to the temperature at the beginning of the selected period. Finally, new simulations were run using this soil model and the solid accumulated precipitation rates. For more details about the soil model, see Wever et al., 2013.

<table>
<thead>
<tr>
<th>Soil layers characteristics</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat capacity</td>
<td>750</td>
<td>J*m$^{-3}$*K$^{-1}$</td>
</tr>
<tr>
<td>Density</td>
<td>2400</td>
<td>kg/m$^{3}$</td>
</tr>
<tr>
<td>Conductivity</td>
<td>1.3</td>
<td>W*m$^{-1}$*K$^{-1}$</td>
</tr>
<tr>
<td>Volumetric water content</td>
<td>12</td>
<td>%</td>
</tr>
<tr>
<td>Volumetric void content</td>
<td>34</td>
<td>%</td>
</tr>
<tr>
<td>Volumetric soil content</td>
<td>54</td>
<td>%</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>+10</td>
<td>°C</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>0.1 to 0.2</td>
<td>m</td>
</tr>
<tr>
<td>Grain size</td>
<td>5 to 35</td>
<td>mm</td>
</tr>
<tr>
<td>Soil albedo</td>
<td>0.25</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.4: Presentation of the ground characteristics for each soil layer.
5.2.2.4. Data output

It was suggested that the distributions of air temperature, the snow surface temperature, the energy balance, the daily maximum amount of liquid water within the snowpack and the minimum value of the sensible flux were statistically different for wet-snow avalanche and non-avalanche days. This suggests that these variables have predictive power (Mitterer and Schweizer, 2013). Thus, these variables seem to be the most important in analyzing snow gliding processes.

The extracted variables from the SNOWPACK simulations used for further analysis were: the percentage of liquid water content of the snow cover, the internal energy change of the snow cover in [kJ m\(^{-2}\)] and the surface input in [kJ m\(^{-2}\)]. Meteorological parameters such as air temperature, snow surface temperature and new snow rates were also used for further analysis (Table 5.5).

<table>
<thead>
<tr>
<th>Extracted SNOWPACK variables</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid water content</td>
<td>%</td>
</tr>
<tr>
<td>Internal energy change</td>
<td>kW/m(^2)</td>
</tr>
<tr>
<td>Surface input</td>
<td>kW/m(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extracted meteorological variables</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Snow surface temperature</td>
<td>°C</td>
</tr>
<tr>
<td>3 days new snow</td>
<td>cm</td>
</tr>
</tbody>
</table>

Table 5.5: Presentation of the extracted parameters for further analysis

The surface input is described at the sum of all fluxes (Figure 5.6). This sum takes into account the following: incoming long wave radiation, net short wave radiation, latent heat flux, sensible heat flux. By adding all these parameters, the surface input can be calculated.

\[
Q_s = LW \downarrow - LW \uparrow + SW \downarrow - SW \uparrow + LE + H
\]  

(5.4)

Where \(Q_s\) is the surface input, \(LW \downarrow\) is the incoming long wave radiation, \(SW \downarrow\) is the incoming short wave radiation, \(SW \uparrow\) is the reflected short wave radiation, \(LE\) is the latent heat flux and \(H\) is the sensible heat flux. All parameters are expressed in [kJ m\(^{-2}\)].

39
The internal energy change is equal to the sum of all of the vertical energy fluxes at the air–snow interface and the soil–snow interface.

\[ U_{\text{int}} = Q_s + G \]  

(5.5)

Where \( U_{\text{int}} \) is the internal energy change, \( Q_s \) is the surface input and \( G \) is the ground heat flux. All parameters are expressed in [kJ m\(^{-2}\)].

Figure 5.6: Illustration of the fluxes used to calculate the surface input of the snow cover (Snowpack documentation, 2012).
5.3. IMAGE ANALYSIS AND ACQUISITION OF GLIDE VALUES

Periods where new glide cracks appeared were identified in the time-lapse data base. Then the images were classified. The photos were manually analyzed gathering several variables. Overall, 117 events were identified, 68 glide avalanches and 48 glide cracks. Appendix 2 provides an example of time-lapse images and glide cracks evolution. Variables describing the glide avalanches were the following: identifier for the event, date and time of the estimated crack opening, date and time of the avalanche, time between the crack and the avalanche, day hour of the crack initiation and day hour of the avalanche (Table 5.6).

<table>
<thead>
<tr>
<th>Glide avalanche variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>Date and time of the estimated crack opening</td>
</tr>
<tr>
<td>Date and time of the estimated avalanche release</td>
</tr>
<tr>
<td>Time between crack and avalanche</td>
</tr>
</tbody>
</table>

Table 5.6 : Presentation of the variables used to describe the snow glide avalanche events.

To describe the glide cracks, the following variables were used: identifier for the event, date and time of the estimated crack opening, day hour of the crack opening, date and time of the end of the observable period, reason of the end of the observation. This classification provided information about periods of glide activity and could be set as a basis for further analysis (Table 5.7).

<table>
<thead>
<tr>
<th>Glide crack variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>Date and time of the estimated crack opening</td>
</tr>
<tr>
<td>Timestamp of the crack initiation</td>
</tr>
<tr>
<td>Date and time of the end of the observed period</td>
</tr>
<tr>
<td>Reason of the end of the observation</td>
</tr>
</tbody>
</table>

Table 5.7 : Presentation of the variables used to describe the glide crack events.
To identify useable events, the quality of the image series was analyzed. Bad quality events were considered as the following: glide avalanche occurring without previous glide crack; events occurring during a very short time period (less than one hour); events developing during bad weather or at night. Furthermore, the picture quality was relevant: glide events occurring with a short angle of incidence between the camera and the slope were not used; events occurring very far from the camera were not considered. From the 117 events previously identified, 44 events were selected, as they seemed to present good analysis opportunities. This sorting resulted into 11 glide events for the Wannengrat site (Table 5.8) and 33 glide events for the Dorfberg site (Table 5.9).

<table>
<thead>
<tr>
<th>Wannengrat</th>
<th>Glide avalanche</th>
<th>Glide crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2010</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2010-2011</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2011-2012</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 5.8 : Description of the number of events per year for the Wannengrat site.

<table>
<thead>
<tr>
<th>Dorfberg</th>
<th>Glide avalanche</th>
<th>Glide crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-2009</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2009-2010</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2010-2011</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2011-2012</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>2012-2013</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5.9 : Description of the number of events per year for the Dorfberg site.
5.3.1. Description of the analysis methods

To quantify glide rates from the time-lapse images, three methods were developed to count the number of dark pixels in the glide area. The first method consisted of an adaptive pixel intensity threshold. For the second method, the images were converted to black/white to count the black pixels in the glide crack. The third method consisted of selecting linear transects of the glide crack and monitoring the evolution of dark pixels along these transects.

5.3.1.1. Dark pixels count in the glide crack with adaptive threshold

The first method was developed by van Herwijnen and Simenhois (2012) and proceeds as follow: first images are converted to grayscale. Then the area around the glide crack is manually determined on the first image where the glide crack appears. This is called the glide crack area. An area near the glide crack containing only snow is then manually delineated. This area is called the reference area. In order to distinguish the exposed ground (dark pixels) from the surrounding snow, a dynamic brightness threshold is then calculated (Figures 5.7 and 5.8). The number of dark pixels in the crack area is determined as the number of pixels with brightness $I < I_{th}$. The adaptive threshold is defined as $I_{th} = \bar{I}_{ref} - 2\sigma_{ref}$, with $\bar{I}_{ref}$ the mean brightness in the reference area and $\sigma_{ref}$ the standard deviation (Van Herwijnen and Simenois, 2012). Changes in the number of dark pixels can be observed over time relating to changes in the size of the glide crack (Figure 5.9).
Figure 5.7: As changes in the pixel distribution is observed under sunny or cloudy conditions, a dynamic threshold is necessary. Examples of a glide crack at the Dorfberg field site under sunny conditions (top left) and cloudy conditions (bottom left). On the right: the corresponding pixel brightness distributions, in blue and red respectively (van Herwijnen, 2012).

Figure 5.8: Overview of the image analysis procedure for a glide crack at the Dorfberg field site (center). The crack area and the reference area containing only snow are outlined. Right: pixel brightness distribution for the reference area. The dashed line indicates the pixel brightness threshold used to distinguish ground from snow. Left: pixel brightness distribution for the crack area. The red bars represent the dark pixels (van Herwijnen, 2012).
Figure 5.9: Number of dark pixels with time for a glide crack that resulted in an avalanche at the Dorfberg site (winter 2011-2012). During nighttime, no image is available, resulting in a gap in the dataset. A sudden increase in the surface corresponds to the release of the avalanche.
5.3.1.2. **Black pixel count in the glide crack**

The second method consisted of increasing the contrast in each cropped image by converting it to black/white (Figure 5.10). Then, an area around the glide crack is manually delineated on the first image where the glide crack appears. The pixel values are then normalized so that zero values are assigned to white pixels and one values are assigned to black pixels. The gray tones are expressed between zero and one. The number of black pixels is then defined as the sum of all values bigger than a certain threshold, which is manually introduced in the computation. The number of black pixels then directly relates to the size of the glide crack and changes in the number of black pixels relate to glide crack opening (Figure 5.11). After having tested several values, the threshold was chosen at 0.45, so that all above values were considered. However, for some analysis, the threshold was adapted, so that the best graphical representation of the glide expansion could be provided.

![Figure 5.10: Illustration of the image processing. First the interesting part is cropped, then the image contrast is enhanced.](image-url)
Figure 5.11: Number of dark pixels obtained with time using the black pixel count method for the same glide avalanche as shown in Figure 5.9. The crack area is delimited in red. During nighttime, no data are available, resulting in gaps in the graphs. The surface values increased suddenly, corresponding to the time the avalanche released.
5.3.1.3. **Black pixel count onto a line**

The third method consisted of counting the number of black pixels onto manually selected transects. It proceeds as follow: first the contrast of each image is enhanced in order to obtain a binary black/white picture (top of Figure 5.12). Then on the last image of the observed event several lines are drawn through the glide crack perpendicular to the slope. Finally the distribution of black pixels onto these lines is automatically counted in each image and the evolution of black pixels can then be observed over time. Increases in the number of black pixels therefore relates to the widening of the glide crack along the line (Figure 5.12).

![Graph showing black pixel count over time](image)

Figure 5.12: Several lines are manually drawn on the image. The expansion over time of the glide crack is expressed by the number of black pixels onto this line. The graph shows the expansion of the glide crack already shown in Figures 5.9 and 5.11. During nighttime, no data are available, resulting in straight lines in the graphs. The sudden increase in the number of dark pixels along the line coincides with the avalanche release.
5.3.2. Test and choice of the analysis method

The three methods were compared using half of the glide events. Seven events from the Wannengrat site and twelve events from the Dorfberg site were used. The effectiveness of each method was mainly determined by comparing the results with visual observations on the images. If snow gliding activity and the opening rates of the cracks from the analysis were deemed realistic, the method was judged as appropriate. This comparison highlighted several important points:

- Contrast enhancement is necessary to achieve good results for the pixel analysis. Black/white images present better results than gray scale images. Increasing image contrast also removed some fluctuations due to changes in brightness during the day.

- Counting black pixels along lines had the advantage of showing glide crack opening over time. It also performed better in areas with vegetation, as the selected image cross-section was not influenced by shade from the surrounded trees. Nevertheless, monitoring changes in the entire glide crack area was more effective than monitoring changes along lines. This was mainly because several events displayed complex shapes with several cracks developing simultaneously and were therefore difficult to monitor using a line. Furthermore, counting black pixels along a line was very sensitive to camera movements.

Considering these two points, counting black pixel over the entire glide crack area was judged the most suitable for glide rate monitoring. Table 5.10 presents the advantages and disadvantages of each method.
**First method: Dark pixels count in the glide crack with adaptive threshold**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface values measurements</td>
<td>Grayscale images present more sensibility to fluctuation in illumination and shade</td>
</tr>
<tr>
<td>Low sensitivity to camera movements</td>
<td>Dark shapes (trees or stones) in the crack area produce an overestimating of the crack area</td>
</tr>
<tr>
<td>Allows the monitoring of complex cracks with irregular shapes</td>
<td></td>
</tr>
</tbody>
</table>

**Second method: Black pixel count in the glide crack**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface values measurements</td>
<td>Dark shapes (trees or stones) in the crack area produce an overestimating of the crack area</td>
</tr>
<tr>
<td>Low sensitivity to camera movements</td>
<td></td>
</tr>
<tr>
<td>Allows the monitoring of complex cracks with irregular shapes</td>
<td></td>
</tr>
<tr>
<td>Increasing the image contrast reduces the noise from shade and changes in illumination</td>
<td></td>
</tr>
</tbody>
</table>

**Third method: Black pixel count onto a line**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing the image contrast reduces the noise from shade and changes in illumination</td>
<td>Widening values limited to single lines; only the activity on these lines is monitored</td>
</tr>
<tr>
<td>Counting black pixel values onto a line reduce noise from surrounding trees or from shade and change in illumination</td>
<td>Difficulty to monitor complex cracks with irregular shape</td>
</tr>
<tr>
<td></td>
<td>High sensitivity to camera movements</td>
</tr>
</tbody>
</table>

Table 5.10: Presentation of the advantages and disadvantages of each method. The percentage of estimated success was calculated by considering the number of analysis that were judged realistic compared to the number of events that were analyzed.
5.3.3. Transformation of the pixel values in metric values

The above described methods provide information on glide rates in pixel values. However, to quantitatively compare the events, a conversion from pixels to meters is required. Using a differential GPS (Trimble GeoExplorer) several points around the glide areas were recorded directly in the field. As the Wannengrat site is not accessible during wintertime, these measurements were only performed at the Dorfberg site.

First, eight areas with glide crack activity were identified at the Dorfberg site (Figure 5.13). These areas contained all the sites where glide cracks and full-depth avalanches were observed each season.

![Figure 5.13: Presentation of the eight sectors that were delimited for recording GPS points. In each sector, three to five GPS points were recorded.](image)

For each sector, three to five GPS points were recorded in the field. These points consisted of obvious features such as trees or small cliffs. For further analysis, only three points are needed, but more points were collected in order to control the method. All points were chosen in the plane of the glide crack slope and would help to define a new 2d basis.

The GPS points were then identified on the time-lapse pictures and positioned in the basic pixel coordinate system. As the three points on the image correspond to the real locations, it was possible to identify a link between the pixel basis and the real basis.
5.3.3.1. Description of the method

The measured GPS points A, B and C have metric coordinates:

\[
A = [A_x, A_y, A_z]
\]

\[
B = [B_x, B_y, B_z]
\]

\[
C = [C_x, C_y, C_z]
\]

The three points therefore define a new linear basis \( \vec{E}_1^*, \vec{E}_2^* \) in the plane of the glide crack:

\[
\vec{E}_1^* = [A_x - B_x, A_y - B_y, A_z - B_z]
\]

\[
\vec{E}_2^* = [C_x - B_x, C_y - B_y, C_z - B_z]
\]

In the image, the three measured points have the following coordinates:

\[
a = [a_x, a_y]
\]

\[
b = [b_x, b_y]
\]

\[
c = [c_x, c_y]
\]

A new basis \( \vec{e}_1^*, \vec{e}_2^* \) can be defined in the image:

\[
\vec{e}_1^* = [a_x - b_x, a_y - b_y]
\]

\[
\vec{e}_2^* = [c_x - b_x, c_y - b_y]
\]

The change of basis-matrix M can now easily be calculated by solving the system:

\[
\vec{E}_1^* = M\vec{e}_1^*
\]

\[
\vec{E}_2^* = M\vec{e}_2^*
\]

This equation is solved numerically. An explicit presentation of the algebraic solution for the matrix M is too complex and would be too long.

Finally each point measured on the picture in pixel basis can be converted to the metric basis \( \vec{E}_1^*, \vec{E}_2^* \) with help of the matrix M. In other words, we are now able to convert the distance in pixel between two points in the picture to a metric distance.
5.3.3.2. Control phase

For each sector, three or more GPS points were recorded. Two vectors were used as a basis to define the coordinate system of each sector. For sectors in which more than three points were measured, the other vectors were used to control the accuracy of the conversion method. The metric distance between the two points was first calculated using the GPS data and compared to the distance derived from the pixel values.

In general, the sectors with the lowest accuracy were the most distant sectors. The measured features (trees or small cliffs) were then hard to precisely identify on the image, resulting in larger errors in the distance estimates. Overall, the accuracy of the conversion method was between 1% and 11% (Figure 5.14).

Figure 5.14: Accuracy of the conversion method for each sector on the Dorfberg site. The error bars are calculated using the standard error.
6. RESULTS

6.1. GLOBAL ANALYSIS

First a global analysis of the observed glide cracks and glide avalanches was performed. As previously suggested by Clarke and McClung (1999), cold temperature events and warm temperature events were analyzed separately. Winter period encompassed the first snowfalls to the end of February and spring encompassed March to the complete snow melt. Overall, 68 avalanches were analyzed, 35 for the winter and 33 for the spring. Only 12 avalanches came from the Wannengrat study site. Appendix 3 presents the annual activity for the 2011-12 winter at the Dorfberg site.

6.1.1. Diurnal variations of glide avalanches release

Figure 6.1 shows the daily distribution of avalanche release during winter time and during spring time. For the analysis, the observed avalanches were classified into different categories. The morning category considers avalanches releasing between dawn and 10:45; the noon category considers avalanches releasing between 11:00 and 13:45; the afternoon category considers avalanche releasing between 14:00 and dusk; the night category considers avalanche occurring at night. Avalanches occurring during a storm or during bad visibility were classified as undefined. The height of the bars corresponds to the percentage of avalanche release for each category. The number above each bar shows the number of recorded avalanches.

The daily distribution of avalanche release showed that during the winter, when the snow cover is cold and dry, no clear tendency can be observed. The percentage of avalanches releasing at nighttime is even highest during this period for the winters 2010/11 and 2012/13. During spring time, when the snow cover is warm and wet, most glide avalanches occur at noon and the activity diminish during the afternoon. Only few avalanches were observed in the morning, and no avalanches were observed at night.
Figure 6.1: Presentation of the release daytime for the analyzed avalanches during winter time (top) and during spring time (bottom). The WAN abbreviation corresponds to the Wannengrat site and the DFB abbreviation corresponds to the Dorfberg site. The total number of observed avalanches N for each site and each winter is written in the legend.
6.1.2. Observed time-lag between crack formation and avalanche release

Figure 6.2 presents the observed time-lag between crack formation and avalanche release for winter time and spring time in hours. Again, 68 avalanches were analyzed, 35 for the winter and 33 for the spring. During wintertime, 85% of all analyzed cracks resulting in avalanches released within 48 hours. However, two cracks released within eight days. 75% of all cracks released within one day, and the median value was 6 hours and 30 minutes.

During spring, 85% of all avalanches released within 12 hours of the glide crack opening. The longest observed time lag between the formation of a glide crack and an avalanche release was of 4 days. 75% of all cracks released within 11 hours, and the median value was 7 hours. The variability is higher during winter than during spring time. The time lag between a crack formation and the avalanche release might be influenced by the low elevation of the study sites, as the main activity of the Dorfberg is observed at 1800m. At low altitude, air temperature is higher and larger daily amplitudes might be expected. The Wannengrat study site is located at higher elevation (average of 2400m) but due to problems with time-lapse cameras, less data are available and the information provided by this study site is then underestimated.

![Box plots showing the observed time-lags between crack formation and avalanche release for winter (left) and spring (right) in hours. The red line represents the median value for each dataset. The box represents the first and third quartile. The upper and lower black lines represent the range and outliers are represented by red points.](image)

Winter (14)  |  Spring (11)
6.2. METEOROLOGICAL AND SNOW COVER PARAMETERS RELATED TO CRACK OPENING

10 avalanches and 10 glide cracks were analyzed at the Dorfberg site. 3 avalanches and 7 glide cracks were analyzed at the Wannengrat site (Table 6.1 and 6.2). Even if more events were previously selected (44 events, see chapter 5.3), changes in illumination, noise, camera movements, new precipitation and misrepresentation of the observed event by the pixel counting program impeded the analysis of more events.

For each event, glide rates were extracted using the black pixel counting method. These resulting glide rates were linked to meteorological and snow cover parameters. The following meteorological parameters were considered: air temperature, snow surface temperature, 3-days sum of fresh snow, surface input (Dreier, 2012). The following snow cover parameters were considered: liquid water content of the snow cover, internal energy (Mitterer et al., 2013). The observed glide cracks and glide avalanche events were classified into cold temperature events and warm temperature events.

<table>
<thead>
<tr>
<th>Wannengrat</th>
<th>Glide avalanche</th>
<th>Glide crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2010</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2010-2011</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2011-2012</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Cold temperature events</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Warm temperature events</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.1: Description of the analyzed events for the Wannengrat site. The number of observed cold and warm temperature events is also presented.

<table>
<thead>
<tr>
<th>Dorfberg</th>
<th>Glide avalanche</th>
<th>Glide crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2011</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2011-2012</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>2012-2013</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Cold temperature events</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Warm temperature events</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.2: Description of the analyzed of events for the Dorfberg site. The number of observed cold and warm temperature events is also presented.
6.2.1. Cold temperature events

Figures 6.3 and 6.4 present the glide crack expansion (red stars) for two observed cold temperature events at the Dorfberg site. Figure 6.3 is related to a glide crack that did not release in an avalanche and Figure 6.4 is related to a glide crack that did release in an avalanche. The liquid water content (top graph, cyan) is expressed in percent, the air and surface temperature (middle graph, respectively blue and cyan) are expressed in Celsius degree. The 3-days new amount of fresh snow (down, yellow) is expressed in centimeters and the internal energy of the snow cover (lower graph, green) is expressed in Kilojoules per square meter. Appendix 4 shows the time-lapse images related to these Figures.

Considering the glide crack (Figure 6.3), following observations were made: from the 6th of January 2012 to the 10th of January, new amount of snow was recorded on the site. Up to 60 centimeters of fresh snow were measured on the Dorfberg site. On the 11th of January, air temperature rose above zero degree, snow surface temperature rose close to zero degree and the liquid water content of the snow cover augmented up to 0.3 %. The internal energy of the snow cover presented values close to 80 kilojoules per square meter. During nighttime, these parameters returned to usual values. On the next day, changes in air temperature, snow surface temperature, liquid water content of the snow cover and internal energy of the snowpack was again observed. Parallel to these changes, the opening of the glide crack was detected.

Considering the glide crack resulting in an avalanche (Figure 6.4), following observations were made: from 22 to 26 December 2011, up to 75 centimeters of fresh snow were measured at the Dorfberg site. On 23 December, air temperature rose above zero degree, snow surface temperature rose close to zero degree and the liquid water content of the snow cover rose to 0.2 %. The internal energy of the snow cover presented values close to 20 kilojoules per square meter. During nighttime and the following days, these parameters returned to usual values. On 25 December, a change in the internal energy of the snowpack was again observed. Coinciding with this change, the opening of the glide crack was detected. On 26 December, the glide crack released an avalanche.

Overall, the following parameters were related to the opening of glide cracks during cold temperature events: precipitations, air temperature, snow surface temperature and liquid water content of the snow cover. For 89% of all considered glide cracks, new snow, positive air temperature, snow surface temperature near zero degree and an increase in the liquid water content of the snow cover were observed before the glide crack opened. For 11% of the observed events, only new snow was observed.

For both glide cracks (Figure 6.3 and 6.4), at the end of the observed period, the following changes were observed: a rise in the liquid water content of the snow cover up to 0.15%, air temperature close to zero degree, a rise in the snow surface temperature and a rise in the internal energy of the snow cover. However, the two events develop in different ways. This suggests that meteorological and snow cover parameters influence the opening of a glide crack but that other parameters are important for determining the avalanche release.
Figure 6.3: A glide crack opened on 12 January 2012 at the Dorfberg field site and was monitored until it was covered by snow on 20 January 2012. Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time.

Figure 6.4: A glide crack opened on 25 December 2011 at the Dorfberg field site and was monitored until it released on 26 December 2011. Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time.
6.2.2. Warm temperature events

Figures 6.5 and 6.6 present the glide crack expansion (red stars) for two observed warm temperature events which occurred in March 2012. Figure 6.5 shows a glide crack that did not release an avalanche and Figure 6.6 shows a glide crack that released an avalanche. The meteorological and snow cover parameters for these events present a different behavior than for cold temperature events (compare with Figure 6.3 and 6.4). Appendix 5 present the time-lapse images for these two events.

Considering the glide crack (Figure 6.5), the following observations were made: on 18 March, 20 centimeters of snow were recorded at the Wannengrat site. Several days before the crack opened, the liquid water content of the snow cover showed diurnal fluctuations and the air temperature was positive. The snow surface temperature showed values close to zero degrees during two days before the glide crack opened. Note that the energy (green line bottom of Figures 6.5 and 6.6) was much higher than for the cold temperature events. On 22 March, a glide crack appeared and it was monitored until 27 March when a snow storm covered the glide crack.

Considering the glide crack resulting in an avalanche (Figure 6.6), the following observations were made: Six days before the glide crack opened, air temperature, snow surface temperature and liquid water content of the snow cover exhibited diurnal variations. Four days before the glide crack opened, the air temperature rose above zero degree during daytime. On 3 March 2013, the opening of the glide crack was detected. Five days later, after two days with a snow surface temperature to zero degree, the glide crack released in an avalanche. Note that the liquid water content of the snow cover reached high values, close to 5%, and that the internal energy of the snow cover reached high values up to 300 kW/m$^2$.

Overall, the following parameters were related to the glide crack opening during warm temperature events: Air temperature, liquid water content of the snow cover, snow surface temperature and internal energy of the snow cover.

It was also observed that for warm temperature events, liquid water content of the snow progressively increases during the events. Considering cold temperature events, the change in liquid water content is observed when the glide crack appears and then the values of liquid water content of the snow cover returns close to zero.
Figure 6.5: A glide crack opened on 22 March 2010 at the Wannengrat field site and was monitored until it was covered by snow on 27 March 2010. Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time. The scatter in the surface values are due to changes in illumination and shading.

Figure 6.6: A glide crack opened on 3 March 2013 at the Dorfberg field site and was monitored until it released on 8 March 2013 (sudden increase in the surface value). Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time.
6.3. OBSERVED TIME LAGS BETWEEN THE OPENING OF GLIDE CRACKS, METEOROLOGICAL AND SNOW COVER PARAMETERS

6.3.1. Time-lags between liquid water content of the snow cover and the opening of glide cracks

Figure 6.7 presents the observed time lag between an increase in the liquid water content of the snow cover and the crack opening for winter and spring. A change of liquid water content of the snow cover was noticed when, from a steady state lasting more than two days, a sudden increase in the liquid water content value was observed. During wintertime, the median time lag value is of 26 hours, and 75% of all glide cracks open 45 hours after an augmentation of the liquid water content of the snow cover is observed. The mean liquid water content value measured when the glide crack appeared was 0.72%. During spring, the median time lag was 120 hours, or five days, and 75% of all cracks opened within 126 hours of a change in the liquid water content of the snow cover. The mean liquid water content value measured when the glide crack appeared was 1.39%.

![Box plots showing the observed time-lags between the first increase in the liquid water content of the snow cover and the appearance of a glide crack for winter (left) and spring (right) in hours. The red line represents the median value for each dataset. The box represents the first and third quartile. The upper and lower black lines represent the range and outliers are represented by red points.](image-url)
6.3.2. Time-lags between new snow and the opening of glide cracks

As new snow was observed before the formation of glide cracks for cold temperature events, time lags between new amount of fresh snow and crack opening were investigated. The time at which the maximum value of three days sum of snow was considered and compared to the time at which the glide crack opened. The mean value was 83 hours, corresponding to 3 and half days. The minimum value was 42 hours and the maximum value was 141 hours.

6.3.3. Time-lags between increase in air temperature and the opening of glide cracks

Figure 6.8 presents the observed time lag between the increase in air temperature and the crack opening for winter and spring. This change was defined as the first time air temperature rose above zero degree, within one week before the glide crack opened. During wintertime, the median time lag value is of 28 hours, and 75% of all cracks opened within 48 hours of an increase in air temperature. During spring, the median time lag is of 70 hours, or five days, and 75% of all cracks opened within 83 hours of a temperature increase.

![Box plots showing the observed time-lags between an increase in the air temperature and crack opening for winter (left) and spring (right) in hours. The change in air temperature was defined as the first time air temperature rose above zero degree within one week before the crack opened. The red line represents the median value for each dataset. The box represents the first and third quartile. The upper and lower black lines represent the range and outliers are represented by red points.](image)

Figure 6.8: Box plots showing the observed time-lags between an increase in the air temperature and crack opening for winter (left) and spring (right) in hours. The change in air temperature was defined as the first time air temperature rose above zero degree within one week before the crack opened. The red line represents the median value for each dataset. The box represents the first and third quartile. The upper and lower black lines represent the range and outliers are represented by red points.
6.4. COMPARISON BETWEEN GLIDE CRACKS AND GLIDE AVALANCHES

6.4.1. Comparison of glide rates

Glide rates from events observed at the Dorfberg site were normalized and compared. Only the glide cracks from the Dorfberg site could be converted from pixel values to metric values. A comparison of the opening rates was made between cracks that did not result in an avalanche and cracks resulting in an avalanche. Figure 6.9 shows the normalized glide rates for cracks and Figure 6.10 shows the normalized glide rates for avalanches. Note that all events were cold temperature events, except for one avalanche (orange line) occurring during March 2013 at the Dorfberg site.

Observed glides rates at the Dorfberg site present life-cycles from one day up to nine days. Glide cracks resulting in avalanches present shorter life-cycles: 80% of the analyzed glide avalanches at the Dorfberg site released after two days (see also chapter 6.1.2). Concerning the form of the normalized glide rates, glide cracks present an exponential shape. Glide avalanches present a more linear shape, and on two of the observed events (green and violet), a period of stagnation is observed before the avalanche release.
Figure 6.9: Normalized glide rates for 10 cracks at the Dorfberg site. These cracks did not result in an avalanche. All presented events are considered as cold temperature events.

Figure 6.10: Normalized glide rates for cracks that released in avalanches. All the data provide from events of the Dorfberg site. Only the orange line represents a warm temperature event occurring during spring 2013. All other events were observed during wintertime.
6.4.2. Comparison of maximum surface values

Figure 6.11 shows the comparison of maximum surface values between glide cracks that did not release avalanches and for glide cracks that released avalanches. The maximum surface value for glide-snow avalanches was measured in the last image before the avalanche released.

For glide-snow avalanches, the median value was 50 m$^2$ and 75% of all values were between 8 and 91 m$^2$. However, values up to 820 m$^2$ were measured. For glide cracks, the median value was 396 m$^2$ and 75% of all values were between 83 and 945 m$^2$. The variability is much higher for glide cracks than for glide-snow avalanches. At the Dorfberg site, the surface is usually eight to ten times smaller for glide avalanches than for glide cracks.

Figure 6.11: Maximum glide crack surface before avalanche release (n=10), and maximum surface for glide cracks without avalanche release (n=10). The red line represents the median value for each dataset. The box represents the first and third quartile. The upper and lower black lines represent the range and outliers are represented by red points.
6.4.3. Avalanche triggering mechanisms

In Figures 6.12 and 6.13 two glide events are shown which occurred at the Dorfberg site during the winter of 2011-2012. Appendix 4b presents the time-lapse images related to Figure 6.12 and appendix 6 presents the time-lapse images related to Figure 6.13. Both glide cracks opened on 25 December 2011, after a period of intense precipitation, high air temperatures and augmentation of the liquid water content of the snow cover. However, the two glide cracks develop into different events, that is, one resulted in an avalanche while the other did not. These two events suggest that meteorological and snow cover parameters are important factors impacting on the opening of a glide crack but that other factors are influencing the triggering of a glide avalanche, such as topography, slope angle, aspect, ground roughness, etc.

Figure 6.14 presents the normalized glide values for these two events. Note that prior to avalanche release, the area of the glide crack was 820m$^2$ while the maximum surface of the glide crack which did not release an avalanche was 950m$^2$, which is very similar. However, the gliding process shows faster values for the glide crack resulting in an avalanche (see also chapter 6.4.1).

It is assumed that fine differences in slope angle and terrain roughness might have high impacts on the triggering of a glide crack. Figure 6.15 shows the glide events drawn on a map of the Dorfberg showing slope angle. Map representation and field observations showed that the glide event take place on a concave roll presenting a rapid decrease in slope angle. The avalanche event takes place on the upper middle of a concave roll presenting a larger steep part.
Figure 6.12: A glide crack opened on 25 December 2011 at the Dorfberg field site and was monitored until it was covered by snow on 29 December 2011. Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time. The scatter in the surface values are due to changes in illumination and shading.

Figure 6.13: A glide crack opened on 25 December 2011 at the Dorfberg field site and was monitored until it released on 26 December 2011. Top: surface of the glide crack (red crosses) and liquid water content of the snow cover (cyan) with time. Middle: Air temperature (blue) and snow surface temperature (cyan) with time. Bottom: Internal energy of the snow cover (green) and 3 days sum of new snow (yellow) with time. The scatter in the surface values are due to changes in illumination and shading.
Figure 6.14: Presentation of the normalized glide crack expansion for a glide crack not resulting in an avalanche (red) and a glide crack resulting in an avalanche (blue) at the Dorfberg site, December 2011.

Figure 6.15: Presentation of the slope angle at the Dorfberg site. The glide event (red circle) is located at 1840 meters and the avalanche event (blue circle) is located at 1800 meters (map: Swisstopo, 2012; modifications: Dreier, 2013).
7. DISCUSSION

7.1. METHODS, INSTRUMENTATION AND FIELD DATA

Using time-lapse photography, we were able to monitor glide crack opening over time. With a simple method based on dark pixel counting, surface augmentation of glide cracks were measured. Obtained glide rates were in line with previous study and observation (van Herwijnen and Simenhois, 2012). Cameras are cheap and easy to use. A shortcoming of the method is, however, that it cannot be used during night time or during bad weather. Furthermore, Shading and changes in illumination provide biases in the estimated glide rates. Access to the study site in winter and presence of recognizable features on the slope are also required to perform GPS measurements used for the conversion of glide rates from pixel unit to metric unit.

To complete the time-lapse photography, seismic sensors were deployed to provide data during night time or during bad weather (van Herwijnen et al, 2013). As the study sites are located very close to the town of Davos, the acoustic data were very noisy. Preliminary results from the seismic sensors are then not conclusive yet because of the noisy data.

7.2. SEASONAL AND DIURNAL VARIATIONS OF SNOW-GLIDING AVALANCHE TRIGGERING

Snow gliding varies during winter. Appendix 3a and 3b shows the glide crack activity for the 2011-2012 winter at the Dorfberg field site.

Considering the time of day at which glide-snow avalanches released, winter and spring were analyzed separately (Figure 6.1). During winter, there was no clear relation between glide-snow avalanche release and the time of day. During spring, however, most gliding activity occurred around noon. This is in line with results presented by Feick et al. (2012) and Dreier (2012). They identified similar variations during spring time, but many studies are in contradiction with this statement (Lackinger, 1987; McClung et al., 1994; Clarke and McClung, 1999). Limited data, biased observation, climatic specificities of the study site or meteorological specificities of the observed winters might have affected the results from previous studies. Considering this presented analysis, it’s very clear that glide crack opening and glide-snow avalanche release relate to time of the day during spring.

Considering the time lags between crack formation and avalanche release, winter and spring were again analyzed separately (Figure 6.2). Results identified shorter time lags between crack opening and avalanche release during spring time than during winter time. Feick et al. (2012) identified time lags of 12 to 72 hours for 80-90% of all analyzed avalanches, which is in line with the presented results. Results showed that time lags between crack opening and avalanche release are on the order of hours. Similar conclusions were derived from previous studies (Clarke and McClung, 1999; Feick et al., 2012). Short time-lags might be due to destabilizations of the sliding slab: if this destabilization cannot be stopped, an avalanche releases. If the sliding snow slab can find equilibrium, the gliding process might slow down or stop, even if opening is still observed. These results are specific to the study site.
7.3. METEOROLOGICAL AND SNOW COVER PARAMETERS RELATED TO CRACK OPENING

Mitterer et al. (2013) identified several variables which are statistically different for glide avalanche and non-avalanche days: the distributions of air temperature, the snow surface temperature, the energy balance, the daily maximum amount of liquid water within the snowpack and the minimum value of the sensible flux. He suggested that these variables have predictive power.

Results showed that glide crack opening during cold temperature events is strongly related to air temperature, augmentation of the liquid water content of the snow cover and solid precipitation (Figures 6.3 and 6.4). These results are in line with previous studies (Clarke and McClung, 1999; Mitterer and Schweizer, 2012; Dreier, 2012). For 89% of all considered cracks, new amount of fresh snow, positive air temperature, snow surface temperature near zero degree and augmentation of the liquid water content of the snow cover were observed before the opening. For 11% of the observed events, only a new amount of fresh snow was observed. For the two cases, the amount of new snow peaked a few days before the glide crack appeared. By the time the glide crack opened, the amount of new snow was back to zero, which means that no new snow had fallen during this period and the new snow had most likely settled.

New snow loads the snow cover, and after the precipitations stops, the fresh snow settles. Settlement is the percentage decrease in the height of new snow as densification proceeds. It is also associated with increased cohesion of the fresh snow. Settlement of new snow appears to be related to avalanche activity (Clarke and McClung, 1999). Loading due to new snow increases creep and viscous deformation. Both effects are relatively slow, which agrees with the observed time lag between loading by new snow and glide crack opening.

Results showed that glide crack opening during warm temperature events is strongly related to air temperature, liquid water content of the snow cover, snow surface temperature and internal energy of the snow cover (Figures 6.5 and 6.6). As suggested by Dreier (2012), solid precipitations play a minor role in warm temperature events and seem not directly related to glide crack opening during spring. During springtime, the presence of liquid water in the snowpack is related to air temperature. Melting produces free water that percolates through the snowpack and acts as a lubricator at the snow-soil interface. Furthermore, when the spring snow cover freezes, surface layers become very strong. This would reduce most of the effects that new snow loading has on the snow cover. Thus, loading by new snow has a minor impact on the snowpack in the spring.

McClung and Clarke (1987) stated that liquid water at the base of the snow cover changes the friction conditions at the snow-soil interface and changes the viscosity of the snow cover. Friction and viscosity are related to fluctuations in glide velocities. Snow viscosity is influenced by air temperature, snow surface temperature and liquid water content of the snow cover. Increasing air and snow temperatures reduces the viscosity of the snow, facilitating its flow. Presence of liquid water at the base of the snow cover reduces the frictional forces between the ground and the snowpack. Viscosity decreases with increasing water content, making creep over the ground-roughness features easier (Clarke and McClung, 1999).
7.4. OBSERVED TIME LAGS BETWEEN THE OPENING OF GLIDE CRACKS, METEOROLOGICAL AND SNOW COVER PARAMETERS

Results highlighted large differences in time lags for cold temperature events and warm temperature events:

Considering the liquid water content of the snow cover during winter time, 75% of all cracks open 45 hours after an augmentation was observed. During spring, 75% of all cracks opened 126 hours after a change in the liquid water content of the snow cover was noticed (Figure 6.7).

Considering the solid precipitation rates for cold temperature events, time lags of 83 hours (3 and ½ days) were observed. As solid precipitations are not related to warm temperature events, no analyze was performed for spring.

Considering the time lags between the opening of glide cracks and rise in air temperature, results showed differences between winter and spring. During winter, 75% of all cracks open 45 hours after an augmentation in air temperature is observed. During spring, 75% of all cracks open 83 hours after a change in air temperature is noticed (Figure 6.8). For winter time, the presented time lags are very similar to the time lags between changes in liquid water content of the snow cover and crack openings. For spring time, the time-lags between changes in air temperature values and crack openings are shorter than for changes in liquid water content of the snow cover and crack openings.

Thus, results suggest that cold and dry snow is more sensitive to changes in meteorological and snow cover parameters, and that warm and wet snow react more slowly to changes in snow cover parameters. The long term effect of settlement is to increase the density, hardness, and strength with depth in the snowpack. The density of the snow is related to its porosity (Clarke and McClung, 1999). Winter snowpacks are more porous than spring snowpacks. Furthermore, in the winter, the snowpack is heterogeneous, and only the upper snow layers are affected by warming and changes in the meteorological conditions. In the spring, the snowpack is homogeneous and changes in meteorological conditions affect the entire snow cover. Propagation time of changes in meteorological variables is higher in a dense snowpack than in a more porous snowpack.

Previous studies focused on time lags between meteorological parameters and avalanche release (Clarke and McClung, 1999), but did not consider the glide crack formation.
7.5. COMPARISON BETWEEN GLIDE CRACKS AND GLIDE AVALANCHES

We were able to monitor glide crack expansion using metric units, which allowed the comparison of opening rates and the area of the cracks between glide cracks and glide avalanches. Results showed that glide cracks resulting in avalanches present short life-cycles, and that 80% of the analyzed glide avalanches release after two days (Figures 6.9 and 6.10). These results are in line previous observations (Feick et al., 2012; Clarke and McClung, 1999). As metric units were used to compare the area of the glide cracks, surface values between glide cracks and glide avalanches short before triggering were compared. Glide crack which resulted in avalanches were generally much smaller that glide cracks which did not result in avalanche release (Figure 6.11). In general, for the Dorfberg study site, large glide cracks didn’t produce avalanches, or only small parts of the glide crack release. These results might be influenced by the topography of the field site. Large cracks, even if presenting larger volume of snow, might present more friction between the stable snow cover and the moving slab and also between the snow-ground interface. No specific analysis sustains this statement.

Two glide events occurring were compared at the Dorfberg site. One glide event resulted in an avalanche and the other not (Figures 6.12 and 6.13). The two events presented similar surface values and the glide crack opening occurred on the same day. Comparing these two events suggest that it’s still unclear which factors influence the triggering of a glide avalanche.

Changes in meteorological and snow cover data are related to crack opening. However, once a destabilization occurred, avalanche release mechanisms seem related to terrain characteristics, soil roughness, internal forces of the snow cover and stauchwall resistance. Gliding is known to occur from 15° slope (Clarke and McClung, 1999) but Dreier (2012) observed that the median slope angle for glide cracks resulting in glide avalanches was between 34° and 40°. This observation is supported by previous work (Newesely et al., 2000; Lackinger, 1987). Furthermore, it was observed that most glide avalanches release in convex rolls (in der Gand and Zupančič, 1966; Dreier, 2012) and that the avalanche starting zones were steeper than the residual areas of a slope (Dreier, 2012). Soil roughness is also an important factor in determining snow gliding. Ground surface roughness highly influences the gliding rates, as smooth snow-soil interface is related to glide activity (Endo, 1984; In der Gand and Zupančič, 1966; Stimberis and Rubin, 2011). Slope angle coupled with surface roughness analysis could provide an important indicator of glide avalanche release probability. Bartelt et al. (2012) found that the material properties and length of the stauchwall play a decisive role in preventing gliding avalanches after the glide crack opens. However, the snow viscosity is an important parameter in determining the stauchwall resistance, and viscosity is dependent of air temperature and snow density. This viscosity increases exponentially with density and decreases with increasing temperature (Scapozza and Bartelt, 2003). Density increase produce snow cover settlement and smaller viscous deformation rates and temperature rise produce higher viscous deformation rates.

Thus, a strong relationship between terrain characteristics, soil roughness, meteorological parameters and snow cover parameters was identified (Dreier, 2013). A full comprehension of these parameters seems relevant in understanding the glide avalanche release mechanisms.
8. CONCLUSION AND OUTLOOK

Time-lapse photography allowed the monitoring of glide crack expansion over time at two different sites close to Davos, Graubünden, Switzerland. A new methodology was developed, allowing the measurement of glide rates. This methodology is based on image enhancement and black pixel counting. When a glide crack opens, the ground is exposed. As the ground is much darker than the surrounding snow, the glide crack can be clearly identified on time-lapse images. Counting black pixels in the crack area allowed the quantification of the crack surface and the monitoring of glide rates over time. Furthermore, a method was developed to convert surface values expressed in pixel units in metric units. GPS points were measured close to the crack area and were identified on the time-lapse image. Comparing the pixel coordinates of the time lapse image with the metric coordinates of the GPS points allowed for the calculation of a transformation matrix. This matrix was then used to perform a change of referential, from a pixel value basis to a metric value basis.

Glide rates were monitored and a link between glide expansion, meteorological and snow cover parameters was established. Even if the presented results may be specific to the investigated area, glide rate monitoring using time-lapse photography presented valuable information on glide crack expansion and improved our understanding of snow gliding process.

First, a seasonal analysis was performed. Results confirmed that snow gliding activity vary through the winter, with two main periods: winter and spring. Cold temperature events are associated with cold and dry snow cover and warm temperature events are associated with warm and wet snow covers. Previous studies suggested that different processes are driving the snow gliding activity during these two distinct periods (Clarke and McClung, 1999). Diurnal variations of glide avalanche release were analyzed for winter and spring. Results showed that during winter time, no clear trend was identified. During spring time, most avalanches released at noon or in the afternoon. Time lags between the crack opening and the avalanche release were analyzed for winter and spring. Results showed that shorter time lags are expected for spring.

Then, meteorological and snow cover parameters were related to glide crack opening. Glide events were again classified into cold temperature events and warm temperature events. Results showed that air temperature, change in liquid water content of the snow cover and solid precipitations play a significant role in glide crack opening for cold temperature events. During spring, air temperature, snow surface temperature, internal energy and liquid water content of the snow cover are the most important parameters in determining glide crack opening. Time lags between increasing air temperature, increasing liquid water content of the snow cover and glide crack opening are much larger during spring, suggesting that an older snowpack is less sensitive to changes in meteorological and snow cover parameters. More inertia was identified between changes in boundary conditions and snow cover response.

Finally, glide avalanches were compared to glide cracks events. Glide rates were compared. Glide avalanches present a much shorter life-cycle than glide cracks, lasting usually less than two days. Glide cracks expand (exponentially) over time, and have a much longer life-cycle. Crack surfaces of glide cracks and glide avalanches (considering the surface short before the triggering) were compared. Glide avalanches presented surfaces eight to ten times smaller than glide cracks. Two glide events occurring at the same period, and thus presenting the same meteorological and snow
cover parameters, were compared. One event developed in an avalanche, and the other did not. This fact suggests that meteorological and snow cover parameters are of high importance in driving the crack opening, but that avalanche release mechanisms is related to terrain characteristics, soil roughness, internal forces of the snow cover and stauchwall resistance.

Since the winter 2012-2013, liquid water content of the snow cover is used by avalanche forecasters at the WSL Institute for snow and avalanche research SLF to identify periods of wet snow avalanche activity (Mitterer et al., 2013). They use liquid water content as one parameter amongst many to write the avalanche bulletin, which informs the public about the current snow and avalanche situation in the Swiss Alps. Based on the results presented here, liquid water content could also be used to identify periods of increased snow gliding.

Based on the encouraging results shown here, it’s believed that time-lapse photography coupled with an analysis of meteorological and snow cover parameters could be a very useful tool for forecasting glide avalanche release. A high temporal resolution of the images is required to obtain good results to monitor glide cracks over time. Thus, timestamps of two to five minutes are ideal. As no data are available during night time or bad visibility, other sensors are required to obtain complete data series. Seismic sensors presented discouraging results in monitoring glide rates, as too much noise is recorded (van Herwijnen et al., 2013). Infrared cameras, potentiometers or in situ GPS markers might be of great use to continually monitor glide rates. However, these two last devices present the disadvantage of a specific installation on each observed glide event. As short time lags between crack opening and glide avalanche release were observed (Feick et al., 2012), these devices would not be of great use. No tests were performed with infrared cameras. Time-lapse camera provides a cheap and flexible alternative. Several glide cracks can be easily tracked at once. Furthermore, by changing the orientation of the camera, glide events that were previously not in the field of view can be monitored. To complete the soil data used as an input for the SNOWPACK model, thermistors could be useful, allowing the monitoring of ground temperature over time.

A global analysis is required to fully understand glide avalanche release, by considering meteorological and snow cover parameters, terrain characteristics and snow pack properties. Slope angle coupled with surface roughness analysis could provide an important indicator of glide avalanche release probability of a certain slope. Furthermore, further analysis of the viscosity of the snow cover could provide valuable information on stauchwall behavior. Viscosity of the different snow layers could also be of great interest in analyzing the gliding behavior of the snow cover. As glide avalanches present a great concern for security management, prevention measures and studies about control methods of glide cracks should be encouraged. Liquid water content of the snow cover, air temperature, snow surface temperature and new snow were identified by previous works as playing a major role in snow gliding (Dreier, 2013; Mitterer et al., 2013). A more comprehensive statistical analysis is needed to determine which parameters relate most to snow gliding. 3D snow cover modelling is required to better understand the subtle differences between glide crack formation and glide-snow avalanche release.
9. BIBLIOGRAPHY


WSL - Institut für Schnee- und Lawinenforschung - SLF. (s.d.). WSL - Institut für Schnee- und Lawinenforschung - SLF. Récupéré sur www.slf.ch
10. APPENDIX

Appendix 1a: Climate diagram for the Weissfluhjoch station for the years 1981-2010 (MeteoSwiss, 2013)

**Climate normals Weissfluhjoch**

*Reference period 1981–2010*

- **Altitude a.s.l.:** 2690 m
- **Geogr. coord.:** 46.83 N / 9.81 E
- **Swiss coord.:** 730615 / 189636
- **Climate region:** Northern and central Grisons

### Climate normals

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<th>Jun</th>
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<th>Dec</th>
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<td>11.9</td>
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</table>
Legend:

**Climate graph:** Graph showing long-term means of monthly mean temperature, mean monthly maximum and minimum temperature as well as monthly precipitation sums of a certain measuring site.

**Table:** Long-term means of monthly mean values and monthly sums of different climatological parameters. Missing values (no measurements or measuring period shorter than 10 years) are labeled as "-".

<table>
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<tr>
<th>Parameter</th>
<th>Description</th>
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<td>monthly mean temperature</td>
</tr>
<tr>
<td>Maximum temp [°C]</td>
<td>monthly mean of daily maximum temperature</td>
</tr>
<tr>
<td>Minimum temp [°C]</td>
<td>monthly mean of daily minimum temperature</td>
</tr>
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<td>Ice days [days]</td>
<td>number of days with maximum temperature below 0° Celsius</td>
</tr>
<tr>
<td>Frost days [days]</td>
<td>number of days with minimum temperature below 0° Celsius</td>
</tr>
<tr>
<td>Summer days [days]</td>
<td>number of days with maximum temperature equal to or above 25° Celsius</td>
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<tr>
<td>Heat days [days]</td>
<td>number of days with maximum temperature equal to or above 30° Celsius</td>
</tr>
<tr>
<td>Relative humidity [%]</td>
<td>monthly mean of relative humidity</td>
</tr>
<tr>
<td>Precipitation [mm]</td>
<td>monthly precipitation sum</td>
</tr>
<tr>
<td>Precipitation [days]</td>
<td>number of days with precipitation equal to or above 1 mm</td>
</tr>
<tr>
<td>Snowfall [cm]</td>
<td>monthly snowfall sum</td>
</tr>
<tr>
<td>Snowfall [days]</td>
<td>number of days with snowfall equal to or above 1 cm</td>
</tr>
<tr>
<td>Snow cover [days]</td>
<td>number of days with snow cover equal to or above 1cm</td>
</tr>
<tr>
<td>Sunshine [h]</td>
<td>measured sunshine duration</td>
</tr>
<tr>
<td>Sunshine [%]</td>
<td>ratio of measured sunshine duration to possible sunshine duration</td>
</tr>
<tr>
<td>Bright days [days]</td>
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</tr>
<tr>
<td>Cloudy days [days]</td>
<td>number of days with sunshine duration less than 20%</td>
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</table>

**Period:** First and last year of analyzed period. Possible gaps in the data series are not separately mentioned.

Homogeneous data series were used to calculate long-term means except for parameters shown in italics. The values can change due to continuous quality control and homogeneity updates. Further information on the Swiss climate and on the homogenization topic can be found on [www.meteoswiss.ch](http://www.meteoswiss.ch)
Appendix 1b: Climate diagram for the Davos station for the years 1981-2010 (MeteoSwiss, 2013)

Climate normals Davos
Reference period 1981–2010

Altitude a.s.l.: 1594 m
Geogr. coord.: 46.81 N / 9.84 E
Swiss coord.: 783514 / 187457
Climate region: Northern and central Grisons

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Precipitation (mm)

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<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<th>Period</th>
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Snowfall (cm)

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<th>Jun</th>
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<th>Nov</th>
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Sunshine [h]

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<th>Period</th>
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<td>149</td>
<td>104</td>
<td>93</td>
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Bright days [days]

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<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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Cloudy days [days]
Appendix 2a: Presentation of time-lapse images provided by the cameras from the Dorfberg field site and the Wannengrat field site. This first dataset presents the Dorfberg slope and the evolution of glide cracks during the 2011-2012 winter. Changes in illumination can be noticed. The presented images are not modified. At the end of the time serie, a storm stopped the observation.
Appendix 2b: Presentation of time-lapse images provided by the cameras from the Wannengrat field site during the 2011-2012 winter. Changes in illumination can be noticed. The presented images are not modified. At the end of the time serie, a storm stopped the observation.
19.01.2012 08:00

19.01.2012 12:00
**Appendix 3a:** Presentation of the 2011-12 glide avalanche activity at the Dorfberg site. Each event is described with the label “Av” and its number (601, 602, 603...). The event is related to the liquid water content of the snow cover and the three day sum of fresh snow (top graph, blue and cyan respectively), the air and surface temperature (middle graph, blue and cyan respectively) and the internal energy of the snow cover (bottom graph, green).
Appendix 3b: Presentation of the 2011-12 glide crack activity at the Dorfberg site. Each event is described with the label “GL” and its number (601, 602, 603...). The event is related to the liquid water content of the snow cover and the three day sum of fresh snow (top graph, blue and cyan respectively), the air and surface temperature (middle graph, blue and cyan respectively) and the internal energy of the snow cover (bottom graph, green).
Appendix 4a: Presentation of time-lapse images provided by the cameras from the Dorfberg field site related to Figure 6.3 (glide crack). The presented images were enhanced and transformed to grayscale pictures. For the analysis, black/white pictures were used, but for better visualization, only the gray scaled images are presented here.

[Images of time-lapse images for dates 12.01.2012 09:00, 13.01.2012 09:30, 14.01.2012 09:30, 15.01.2012 10:00, 16.01.2012 08:30, 17.01.2012 08:30]
Appendix 4b: Presentation of time-lapse images provided by the cameras from the Dorfberg field site related to Figure 6.4 and Figure 6.12 (snow-gliding avalanche). The presented images were enhanced and transformed to grayscale pictures. For the analysis, black/white pictures were used, but for better visualization, only the gray scaled images are presented here.

25.12.2011 09:00

25.12.2011 14:30

25.12.2011 16:15

26.12.2011 08:30

26.12.2011 12:00

26.12.2011 12:30
Appendix 5a: Presentation of time-lapse images provided by the cameras from the Wannengrat field site related to Figure 6.5 (gliding crack). The presented images were enhanced and transformed to grayscale pictures. For the analysis, black/white pictures were used, but for better visualization, only the gray scaled images are presented here.
Appendix 5b: Presentation of time-lapse images provided by the cameras from the Dorfberg field site related to Figure 6.6 (snow-gliding avalanche). The presented images were enhanced and transformed to grayscale pictures. For the analysis, black/white pictures were used, but for better visualization, only the gray scaled images are presented here.

![Images of time-lapse images](image)

04.03.2013 08:00  04.03.2010 16:00

05.03.2013 08:00  05.03.2013 16:00

06.03.2013 08:00  06.03.2013 16:00
Appendix 6: Presentation of time-lapse images provided by the cameras from the Dorfberg field site related to Figure 6.12 (snow-gliding avalanche). The presented images were enhanced and transformed to grayscale pictures. For the analysis, black/white pictures were used, but for better visualization, only the gray scaled images are presented here.