MONITORING SNOW CORNICE DEVELOPMENT USING TIME-LAPSE PHOTOGRAPHY

Alec van Herwijnen[1]* and Charles Fierz[1]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: A snow cornice is an overhanging mass of snow which generally forms on the lee side of ridges. Cornices can present a substantial snow avalanche hazard as they can trigger avalanches when they break. While the hazard posed by cornices has long been recognized and they are extensively controlled in avalanche operations, little research exists on cornice formation and failure. In this study, we used a time-lapse camera to monitor the growth and failure of a cornice during the 2013-2014 season. Images were taken at five minute intervals at a site which is instrumented with several automatic weather stations above the town of Davos, Switzerland. To compare the growth of the cornice with local meteorological variables, we developed a method to automatically track the horizontal extent of the cornice based on converting the images to a binary format. Our results show that cornice growth only occurred during periods of moderate to high winds during or soon after snowfall. During the season we only observed a few small cornice failures, which mainly occurred after periods of rapid cornice growth. Finally, we compared our observed cornice extent to the wind drift index calculated by the snow cover model SNOWPACK. The agreement between both was remarkable, suggesting that the SNOWPACK wind drift index can be used to quantify regional cornice growth.

KEYWORDS: cornice growth, snow cover modeling, time-lapse photography, avalanche forecasting.

1. INTRODUCTION

Wind can transport large amounts of snow, changing the local distribution of snow, as well as the stratigraphy and the stability of the snow cover. After precipitation, snow transport by wind is widely considered the major factor in determining local avalanche danger and snow slab avalanches can often be triggered from snow drifts. While measurement devices have been designed to measure snow drift (Chritin et al., 1999), for operational avalanche forecasting snow transport is mainly assessed through visual observations of blowing snow over mountain ridges.

Snow transport by wind also results in the formation and growth of snow cornices, overhanging masses of snow, which generally form on the lee side of ridges. Thus, observing the growth of cornices can provide direct indication of snow transport by wind. Furthermore, cornices can also present a substantial snow avalanche hazard, as they are known to trigger avalanches when they break. Nevertheless, little quantitative research exists on cornice growth and failure.

Recently, Vogel et al. (2012) published the first comprehensive study on meteorological factors controlling the growth and failure of cornices. Over the course of two winter seasons, they monitored cornice formation and break off using a combination of time-lapse photography, detailed observations and hourly meteorological data. They showed that cornice accretion typically occurred for a mean wind speed of 12 m s^{-1}, with a mean prevailing wind direction from the SE, perpendicular to the ridgeline. Cornice scouring, on the other hand, was mostly associated with extreme wind speeds. Furthermore, they observed 180 cornice failures, mostly towards the end of the snow season in June. Cornice failures were almost always preceded by the appearance of cornice cracks, which generally appeared four to five weeks prior to cornice failure.

In the research outlined in this paper we followed a similar approach for studying the development of a large cornice above an avalanche start zone in the Swiss Alps. However, while we are also interested in linking local meteorological data to cornice dynamics, our main goal is to investigate whether the numerical snow cover model SNOWPACK (e.g. Lehning et al., 1999) can be used to describe cornice development during an entire winter season.

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* *Corresponding author address:*
Alec van Herwijnen, WSL Institute for Snow and Avalanche Research SLF, Davos, Swithzerland;
tel: +41-81-4170-161;
email: vanherwijnen@slf.ch

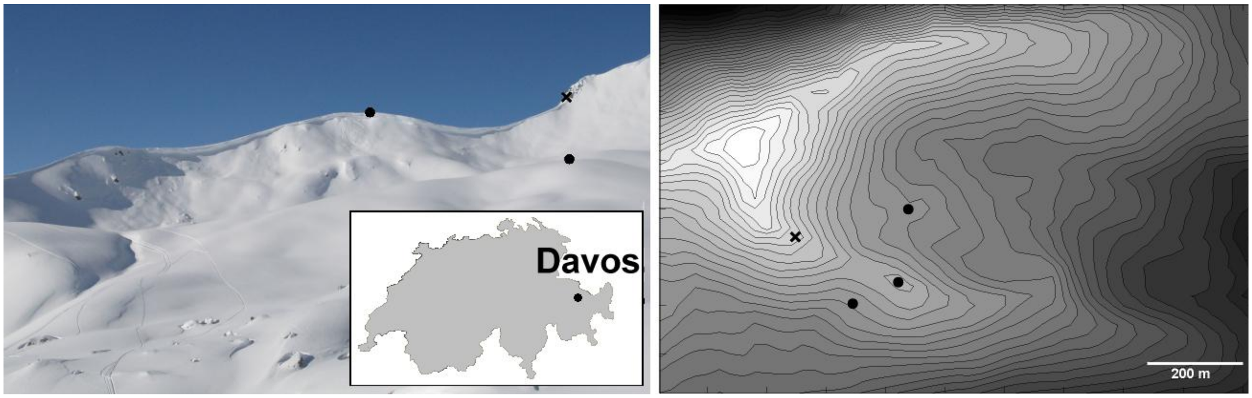

Figure 1: Overview of the field site above Davos, Switzerland. Left: A photo of the ridge where we monitored a large cornice. The location of automatic weather stations (dots) and the automatic camera (cross) is also shown. Inset: location of the field site in Switzerland. Right: contour elevation map (50 meter contour lines) showing the location of three local automatic weather stations (dots) as well as the camera (cross).

2. METHODS

2.1 Site and instrumentation

During the winter 2013-2014, we monitored the development of a large cornice at our Wannengrat field site in the eastern Swiss Alps (Figure 1). The field site is located approximately 2.5 km above Davos and is instrumented with several automatic meteorological stations (AMS) providing continuous meteorological data, including air temperature, wind speed, wind direction and snow height.

At the field site, every winter a large cornice forms on the lee side of a ridge located at an elevation of 2475 meter. Furthermore, small to medium wind slabs frequently release on the steep NE facing slope behind the ridge. In the fall of 2013 we therefore installed an automatic camera on a rocky outcrop overlooking this ridge. Images were recorded every 5 minutes and stored locally on a low power single board computer (Raspberry Pi). Every hour, the images were then transferred to the SLF through a long distance wifi link.

2.2 Image analysis

To determine the development of the cornice, the images from the automatic camera were analyzed in a quantitative way. The image analysis work flow consisted of three steps (Figures 2 to 4):

1. Automatically identify if the image is of sufficient quality to ensure that the cornice is clearly visible. This was done by comparing the brightness of pre-defined image areas with objects of various brightness, such as trees, sky, and snow. On images with good visibility, the total brightness of the reference objects is similar. However, when visibility is limited, for instance during a snow storm, the total brightness is substantially different (Figure 2).

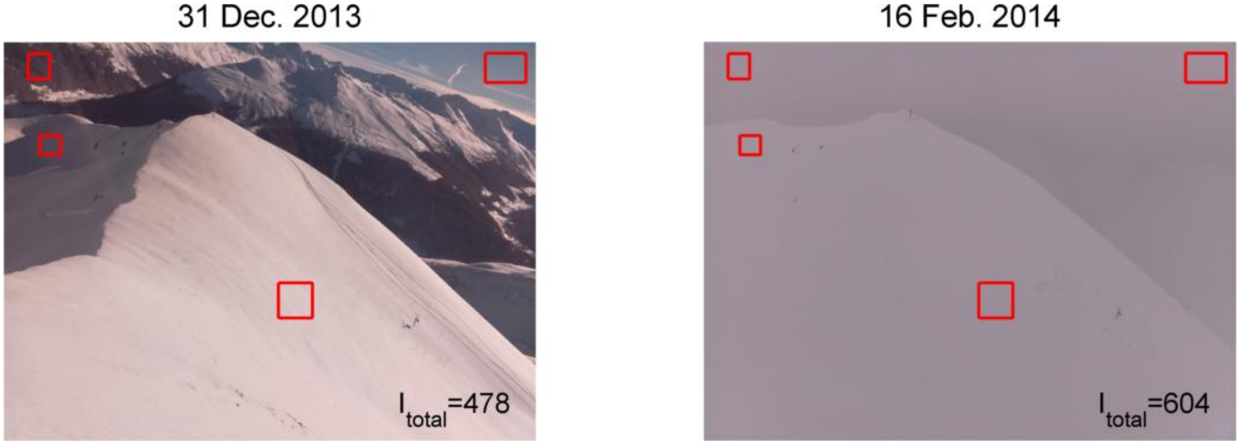

Figure 2: Method used to automatically identify images where the cornice was clearly visible. Left: image with good visibility showing the manually selected areas containing sky, trees, snow and shaded snow (red squares) as well as the total brightness (I_{total}). Right: same for an image with poor visibility.

Figure 3: Method used to correct for camera movement. Top: reference image showing the fixed reference object (red square). Bottom: images of the reference object on two different days. The top of the mast (red and green square) moved considerably between both images.

2. Rotate and translate the images to correct for camera movement due to wind and thermal expansion of the camera case. This was achieved by performing an image correlation analysis to determine the displacement of the image relative to the first image, using a predefined fixed object as reference (Figure 3).
3. Determine the location of the edge of the cornice and calculate the mean width. This was done by first converting the images to black and white and then rotating it so that the edge of the cornice was more or less a horizontal line in the image. The location of the edge of the cornice was then determined as the distance, in pixels, from the bottom of the image to the last white pixel (Figure 4).

2.3 SNOWPACK wind drift index

To verify if cornice growth can be reproduced using a numerical snow cover model, we used the wind drift index from SNOWPACK (Lehning and Fierz, 2008). The index requires input from a wind-sheltered automatic weather station and a wind speed measurement from a wind exposed site. Here, we briefly describe how the wind drift index is calculated (for more details, see Lehning and Fierz (2008)).

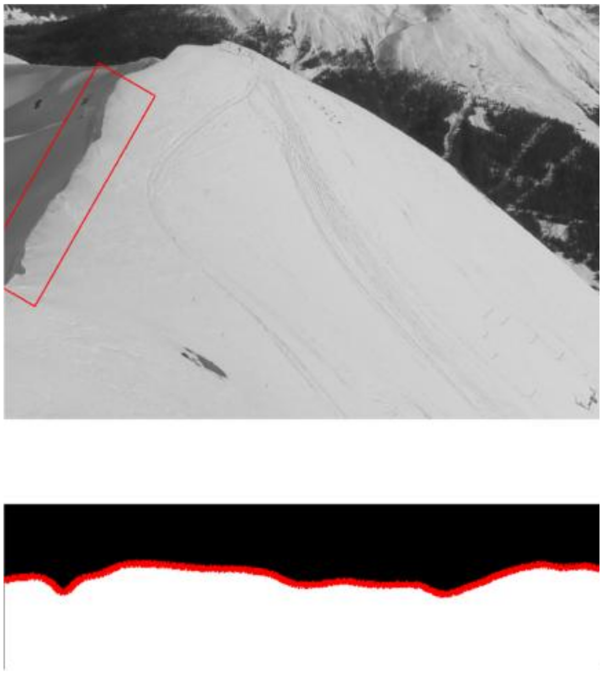

Figure 4: Method used to determine the width of the cornice. Top: original image corrected for camera movement. The red square shows the part of the cornice we analyzed. Bottom: cornice section converted to black and white and rotated. The red line shows the location of the edge of the cornice.

First, a local threshold velocity is determined based on the local snow characteristics, such as sphericity and bond to grain radius ratio. This threshold velocity is a measure of the drag that the atmosphere has to exert on the snow surface to start transporting snow. Second, using this threshold velocity and the locally measured wind speed, the mass transport rate of snow is determined. Finally, the local snow mass transport rate is translated into cm of deposited wind drifted snow on a lee side slope. This is done by assuming that the mass of transported snow is distributed over a slope of arbitrary length of 70 m.

3. RESULTS AND DISCUSSION

Due to technical and logistical problems we were not able to install the camera before mid December. We therefore did not document the formation of the cornice early in the season. By 12 December 2013, when we installed the camera, the cor nice had already grown to a substantial size (top image in Figure 3). Nevertheless, over the re-

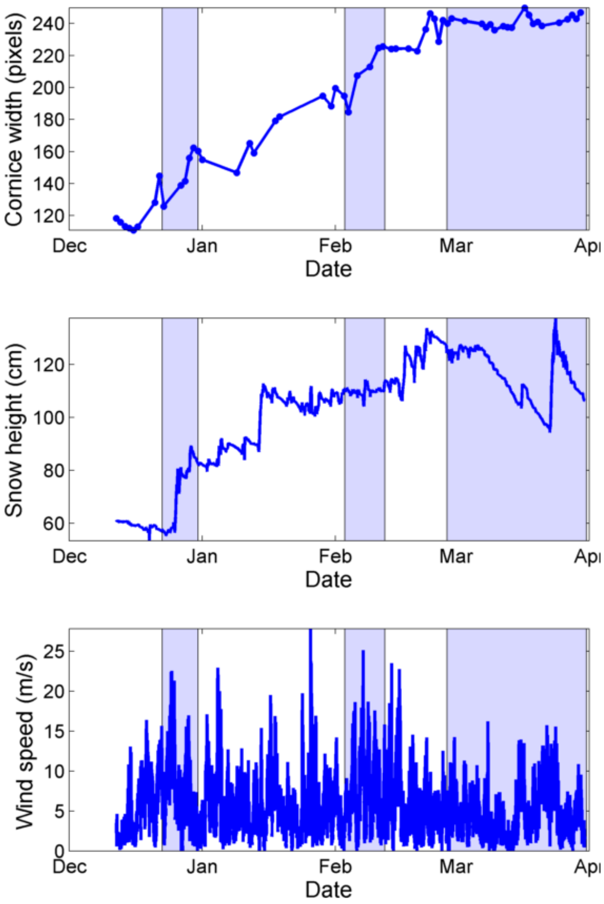

Figure 5: Top: cornice width with time. Middle: snow height with time. Bottom: wind speed with time. The blue shaded areas highlight three periods that are discussed in more detail.

mainder of the season, we were able to determine the width of the cornice on 933 images between 12 December 2013 and 30 March 2014, during which time the cornice continued to grow substantially (top in Figure 5).

At first glance, the development of the cornice was closely related to measured snow height (compare top and middle of Figure 5). However, when examining both parameters more carefully, some important discrepancies stand out, highlighted by the three shaded blue periods in Figure 5. During the first period, at the end of December, the cornice grew after a snowfall, as one would expect. However, during the second period, at the beginning of February, the cornice grew without any significant snowfall. Finally, during the third period, spanning the month of March, the cornice did not change much in size, despite large fluctuations in snow depth.

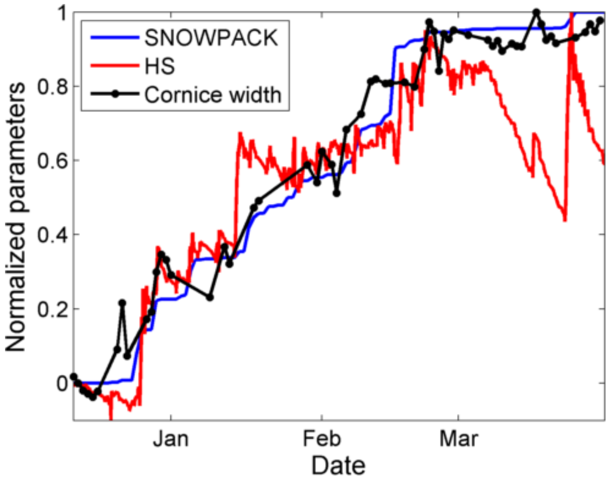

Figure 6: Normalized cumulative wind drift index (blue line), normalized measured snow depth (red line) and normalized cornice width (black line) with time.

Clearly, more snow does not necessarily equate to cornice growth. Similarly, more wind does not always coincide with cornice growth (e.g. early January in Figure 5). Evidently, snow transport by wind is not simply a matter of snowfall in combination with wind, and a simple wind drift index based on changes in snow height times wind speed did not correlate well with observed cornice growth (not shown). This begs the question: how does the more physically based wind drift index from SNOWPACK correlate with our observed changes in cornice width? As can be seen in Figure 6, the answer is: very well. Indeed, the normalized cumulative wind drift index calculated at a nearby weather station (blue line in Figure 6) followed the normalized width of the cornice (black line in Figure 6) very closely. The correlation between the cumulative wind drift index and cornice width was nearly perfect (Pearson r=0.99, p<0.01), a clear improvement over the correlation with snow depth (red line in Figure 6; Pearson r=0.91, p<0.01).

4. CONCLUSIONS AND OUTLOOK

In this study we presented an image processing method to determine fluctuations in the width of a cornice using time-lapse photography. Our results show that reliable width estimates can be obtained in this manner. However, in the future we will improve our method by georeferencing the images to obtain quantitative width estimates in meters rather than pixels.

Comparison of cornice width with meteorological parameters showed that cornice growth was generally associated with increased snow height and wind. While overall the correlation between snow height and cornice width was good, several cases of cornice growth were observed in the absence of snowfall and vice versa. On the other hand, the more physically based wind drift index from SNOWPACK exhibited a better correlation with cornice width estimates. Overall, our results clearly show that the wind drift index can be used to estimate cornice growth over a season, and thus provides a reliable index for the amount of snow transported by wind. However, while our results are very encouraging, we want to point out that we did not observe any cornice failures during the winter. Thus, at this point we cannot make any statements with regards to critical growth rates or meteorological conditions associated with cornice failure. We will therefore continue to monitor cornice growth at our field site in Switzerland, and hopefully gather some data on mid-winter cornice failures.

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