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Interactive comment on "Cornice dynamics and meteorological control at Gruvefjellet, Central Svalbard" *by* S. Vogel et al.

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1 I agree with Kalle Kronholm that the focus of study could be made clearer. Though avalanches triggered by partial cornice collapse are mentioned, it appears that these are relatively small and non-threatening, so their mechanism of release is not the primary concern. Since these smaller cornice breaks are common triggers of sizable avalanches in other regions, it would be good to include some clarification in the introduction. It appears that avalanches triggered by the entire cornice releasing along the cornice crack are the focus, and the main source of threat to the settlement. It would be helpful to compare the size and number of non-cornice-triggered avalanches, those triggered by partial cornice breaks, and those triggered by full cornice collapses. It would also be good to have some description of how many of these cornice falls are

triggering slab avalanches, and how many are simply triggering and entraining loose snow, if known. Also some discussion of non-cornice-triggered avalanches would be useful in the introduction. Are the slabs triggered by wind-loading, rain, or other mechanisms an important threat? A brief discussion of historical avalanches affecting the settlement area, and their causes, might be appropriate; with the understanding that remote areas often have little historical information available, and that there is little evidence left behind from historical avalanches in areas without trees.

Our study showed that the collapse of entire cornices represent the main source of threat to the settlement. The size of the avalanche is primarily controlled by the collapsed cornice, but these failures may also entrain additional snow in the avalanche path. We therefore use the term 'cornice fall avalanches'. The collapsed cornice breaks up into smaller pieces and fan out with single cornice blocks reaching runout distances significantly longer than the main mass of snow. Using automatic time-lapse photography we did not observe any sizeable avalanche in our study area which was not attributed to any cornice failure in the course of the two snow seasons. Only three out of 180 cornice failures triggered a secondary slab avalanches below. Here the amounts of additionally entrained snow were insignificant. Clearly, a cornice triggered slab avalanche in April or May when the snow cover on the slope below is thickest, may involve considerable amounts of snow. Still, this was not observed in the study area in recent years, but in adjacent areas. A study by Eckerstorfer and Christiansen (2011a) determined the best suitable meteorological variables for forecasting natural slab avalanches. The authors found that precipitation and snowdrift 24, 48 and 72 h prior to an avalanche and non-avalanche day were the best predictors. There are very limited records of historical avalanches in Svalbard, other than extreme slush avalanches (Jahn, 1976) and these did not happen on the studied slope. In earlier years when this part of the settlement was built, explosives were used to prevent the built up of larger cornices at the crest of the slope. Still, there is geomorphological evidence, that the settlement Nybyen is built on cornice fall avalanche deposits, implying that extreme events can definitely destroy infrastructure.

Jahn, A., 1976. Contemporaneous geomorphological processes in Longyeardalen, Vestspitsbergen (Svalbard). Biuletyn Peryglacjalny, 26, 25.

Eckerstorfer, M., Christiansen, H.H., 2011a. Relating meteorological variables to the natural slab avalanche regime in High Arctic Svalbard. Cold Regions Science and Technology, 69(2-3), 184-193.

2 In the abstract, I would add to the comment on "induced by pronounced air temperature fluctuations" an indication of whether those fluctuations included temperatures above the freezing point.

The pronounced air temperature variations are caused by low pressure systems reaching Svalbard, bringing warm and moist air masses. Temperatures might reach above freezing and lead to midwinter rainfall events.

3 If large cornices dropping are the primary threat to settlement, it seems that jet roofs, drift fencing, or other cornice-reduction methods might be more useful than forecasting and evacuation, given the forecast accuracy limitations with a time window of weeks for cornices to drop after first showing visible signs, and that not all cracks resulted in releases and not all releases were preceded by cracking. Annual return for slides capable of damaging housing is certainly high enough to merit consideration of structural approaches. Brief discussion of possible mitigation approaches based on the study's results, including studies that might refine forecasting accuracy, would add value.

Please also see our reply on Kalle Kronholm's question 2.

Besides structural protective measures, a continuation of our cornice failure database including crack initiation dates and eventual cornice failures with their overall meteorological conditions would without doubt furthermore refine the forecasting accuracy. Clearly, at this stage our forecasting accuracy is not adequate to ensure safety of life and infrastructure, but our results are a first step towards a better predictability of cornice fall avalanches based on meteorological conditions. Hopefully presenting

the cornice processes and their potential effects to the landscape below, will increase the awareness that cornice reducing installations might be useful.

4 The two winters studied yielded a sufficient number of events for analysis, but is there any information available on how representative a sample those two winters were of the typical range of variability for weather and avalanche activity? A brief comparison with long-term weather records and any known climate cycles would be great.

The very detailed monitoring of avalanche activity in our study area by automatic cameras started in the winter 2008/2009. Since 2005/2006 general observations on avalanche activity in the surroundings of Longyearbyen including our study area were carried out (Vogel, 2010). These earlier observations of cornice fall avalanches affirm an annual return period of cornice fall avalanches categorized as “D3R4” avalanches at the study site. Despite this, the avalanche derived fans indicate higher magnitude avalanches in the past. In general, cornice fall avalanches constitute 45 % of all avalanche releases in the Longyearbyen area. This is due to the extensive plateau mountain topography and a prevailing winter wind direction (Eckerstorfer and Christiansen, 2011b). These authors observed 19 avalanche cycles in the period 2006-2009 in which over 80 % of all avalanches released. The main cause was low-pressure systems reaching Svalbard, resulting in air temperature fluctuations and snowstorms. As low-pressure frequency is modeled to decrease in the North Atlantic (Zahn and von Storch, 2010), less avalanche activity can be expected. Therefore it can be concluded, that cornice fall avalanches will become relatively seen even more dominant (Eckerstorfer and Christiansen, 2011b). The timing of cornice fall avalanches at the study site is also comparable to the overall timing of releases in the Longyearbyen area, with maximum activity between April and June (Eckerstorfer and Christiansen, 2011b). These data is based on data collection in the period 2007 – 2010. Two extreme mid winter slush avalanche events were observed in January 2010 and March 2011. Both were triggered by slow passing low-pressure systems, bringing well above 0°C air temperatures and 100 year record precipitation over an extended period (Eckerstorfer and

Christiansen, in press). Four potential slush avalanche periods were found with similiar meteorological conditions, clustering all in the mid 1990s, when analyzing the entire almost 100 year meteorological record. The authors could not find any correlation though between rising mean annual air temperatures and extreme event frequency (Eckerstorfer and Christiansen, in press)

Zahn, M., von Storch, H., 2010. Decreased frequency of North Atlantic polar lows associated with future climate warming. Nature, 467(7313), 309-312.

Vogel, S., 2010. Cornice accretion, cracking and failure along with their meteorological controls at Gruvefjellet, Central Svalbard, UiO / UNIS, Oslo / Longyearbyen, 102 pp.

Eckerstorfer, M., Christiansen, H.H., 2011b. Topography and meteorological control on snow avalanching in the Longyearbyen area, central Svalbard 2006-2009. Geomorphology, 134(3-4), 186-196.

Eckerstorfer, M., Christiansen, H.H., in press. Meteorology, topography and snowpack conditions causing extreme mid-winter slush and wet slab avalanches in High Arctic maritime Svalbard. Permafrost and Periglacial Processes.

5 Page 2281 - In the introduction, it might be more descriptive to refer to cornices as being shaped like a breaking wave, rather than just as “wedge-shaped”.

We refer to the definition by Montagne et al. (1968) that cornices are defined as wedge-shaped projections of snow. But we would be happy to receive a reference to the term “breaking wave”.

Montagne, J., McPartland, J.T., Super, A.B. and Townes, H.W. 1968. The Nature and control of snow cornices on the Bridger Range, southwestern Montana: Alta Avalanche Study Center, Miscellaneous Report No. 14.

6 Page 2291 - The problem of creating a reference point to measure snow motion is common to cornice, creep, and glide crack studies. Stakes as used are a simple and robust solution, but they can move in the snow under wind, creep, or melt, and the

motion of the part of the snow mass they are connected to may or may not represent the movement of the cornice overall.

Please also see our reply on Kalle Kronholm’s question 3

We are aware that our cornice crack measurement setup poses some limitations as a consequence of the site specific conditions and the requirement of manual measurements, which we also state in the paper. We excluded the very last measurements when melting conditions affected the position of both stakes. Other than these measurements towards the very end of the snow season, we considered the stakes position as stable as these were installed on close to horizontal terrain and the snowcover on the windswept plateau is particularly dense. Our coverage by automatic time-lapse photography proved that the positions of snow stakes along the plateau edge are stable throughout the snow season. Clearly, in sloping terrain snow creep would affect the position of installations inserted into the snowcover.

7 Page 2292, line 23 - I am curious as to the range of these “increasing air temperatures”, and would like more detail here. How close to freezing? Above or below? If above, for how long?

The pronounced midwinter warm spells are a consequence of the extreme maritime setting of Svalbard, in which low-pressure systems bring relatively warm and moist air masses. Wind speeds during snow storms are in particular high. Temperatures might reach above freezing conditions. In the 2008-2010 period the most pronounced midwinter warm spell occurred between 13-15 January 2010, with maximum temperatures of +3.5°C and 34 mm of rain at sea level. It is discussed in the first few lines on page 2297 later in the paper. Reference to this extreme slush avalanche event is Eckerstorfer and Christiansen (in press).

Eckerstorfer, M., Christiansen, H.H., in press. Meteorology, topography and snowpack conditions causing extreme mid-winter slush and wet slab avalanches in High Arctic maritime Svalbard. Permafrost and Periglacial Processes.

11 Page 2298 - Intriguing finding that snow and increasing temperatures initiated cracking but not collapse. Useful understanding of process. How about smaller breaks; were they more common during storms, or were they obscured by cornice-building and drifting snow that made them hard to detect visually?

The vast majority of smaller failures took place towards the end of the snow season. These failures display the collapse of previously cracked cornices, or cornice sections such as scarp and pillow. Under the influence of rising temperatures failure of the cornice leading edge and the accretion face leads to a rounding of the remaining cornice mass. We did not observe a close relationship of enhanced cornice failures as a direct consequence of storm events. At times we observed very small failures of the cornice scarp and pillow after storm events, probably resulting from loading by overshot snow.

12 Page 2299 - The observation that rock buttresses on the sides supported some cornices suggests that in situations where an excavator could be brought to the ridgeline, and where the rock is loose enough for digging, the topography might be reshaped into smaller basins with buttresses shaped to wedge cornices in place. It sounds like the rock at this site may be too hard for easy excavation, but in the Alaskan Arctic, frost action is so intense that many rock outcrops are shattered and have more rubble than solid rock. Re-contouring the ridgeline above settlements or developments could be a practical mitigation solution in some locations.

Re-contouring the ridgeline could be a practical mitigation solution in some locations with easier access to the mountain ridgeline. But in turn this may also alter the slope stability which may cause secondary consequences such as enhanced rock fall events. There are oral reports that manually removing the cornices at an early stage could also be a practical mitigation solution.

13 Typos Page 2300- line 25

“Despite large air temperature variations the cornice crack opening revealed a linear opening distance, which we attribute to constant snow creep at the cornice foot, were

the temperature conditions remain steady due to thick snow covering insulation and thus enabling the freezing onto the backwall in the permafrost environment.”

Interactive comment on The Cryosphere Discuss., 5, 2279, 2011.