The influence of debris on the ablation rate of the snowpack at the base of the Sulztal glacier, Austria

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Abstract
Over the next century, ablation rates will contribute significantly to the impacts of climate change. The majority of studies have focused mainly on glacial ablation rates, with little attention towards snowpack melting. In order to quantify the ablation of the Sulztal glacier snowpack, the effects of three main variables; debris cover and non-debris cover, debris clast size and black body radiation were measured. Observations were made over a week and ablation measurements were taken overnight. It was concluded that debris covered snowpacks melted faster than non-debris covered ($t=-3.4515$, $df=7.0369$, $p = 0.01058$). With increased clast size ablation rates fell ($p=0.06949$, $r^2=0.6255$). Increasing distance away from the surrounding black body caused ablation rates to fall ($p=0.0298$, $r^2=0.9118$).

Keywords: Debris cover, Ablation, Snowpack, Austrian Alps

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1.Introduction

It is acknowledged that glaciers contribute to hydrological systems in alpine areas, specifically through the storage of water and the subsequent release in the melt season. Although ice cover in the Alps is a fraction of the size of global ice reservoirs, this region is vital to research in the context of climate change (Fischer et al., 2015). Despite predicted sea level rise caused by the melting of alpine glaciers being negligibly small (0.24m), the relative contribution globally in the next 100 years will be significant (Church et al., 2001). Many papers have stressed the economic importance of snow, particularly in aspects such as tourism and water management (Beniston et al., 2003; Barnett, Adam and Lettenmaier, 2005; Verbunt et al., 2003). Furthermore, the water supply of one-sixth of the world's population depends on snowpacks and glaciers, highlighting their anthropogenic importance (Cline, 1997).

When ice melt occurs, the majority takes place on the surface, with weather acting as a strong controlling factor; short-wave radiation emitted by the sun causes direct surface melting. Mountainous areas characterized by high relief and abundant debris play a vital role in the radiation receipt locally (Hubbard and Glasser, 2005). 99% of terrestrial radiation is emitted in the form of long-wave radiation (McClung and Schaerer, 2006) and causes a significant reduction in snow and ice cover. Similarly, it has been argued that the debris covering glaciers and snowpacks can act as an insulating layer, which prevents the underlying ice and snow from melting, reducing ablation (Krainer and Mostler, 2002). However, this relationship is complicated as there is strong variation in glacial ablation rates between debris cover of different clast sizes with smaller sizes generally found to be greater insulators (Pelto, 2000).

Due to the rapid retreat of alpine glaciers since the Little Ice Age (Watson, 2017) accessibility is becoming increasingly more difficult. Furthermore, there have been many academic studies into the ablation rates of glaciers (Takeuchi et al., 2000; Nakawo and Young, 1981; Reid et al., 2012; Collier et al., 2015; Anderson and Mackintosh, 2012) with little focus on snowpacks, in particular those at higher altitudes (Cline, 1997). As a result of this literature gap, this study places emphasis on the ablation of snowpacks rather than glaciers. There is also a lack of published data on supraglacial debris properties (Nicholson and Benn., 2012) for example grain size (Juen et al., 2014). Juen et al., (2014) stated that smaller single grains of debris, when overlying ice, absorb more heat than the ice due to their lower albedo, melting the ice underneath as they transfer energy.

The aim of this study is to investigate the differences in ablation rates between snowpacks of different debris covers.

2. Hypotheses

1. Debris covered ablation will be significantly higher than uncovered ablation; within this investigating the influence of clast size.

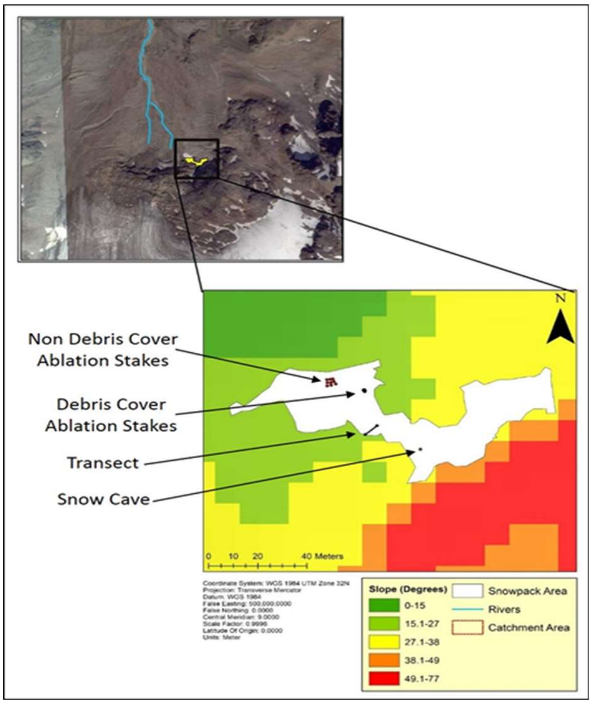

Figure 1- The location of the snowpack in relation to the Sulztal glacier, with the topography around the fieldwork site indicated along with field experiment locations.

2. There is a significant relationship between ablation rates and distance from blackbody emitters.

3.Methodology

Fieldwork took place at the southern end of the Sulza Valley, Austria (N.5208217° E.0658293 ° 32T UTM) at an altitude of 2,512m. The snowpack was located at the base of the Sulztal glacier, facing North, with an estimated area of 2834m^2. The snowpack was found to be concave, overlying the uneven topography of a deposited boulder field (Figure 1). Week-long observations showed the snowpack to be melting particularly quickly in the centre, where a large area of underlying rock was evident, and at the edges where large amounts of undercutting occurred.

Figure 2- The snowpack being studied taken facing south (Photograph by K. Thompson).

According to Hubbard and Glasser (2005), a suitable method to measure snowpack ablation is to insert ablation stakes into the snow as fixed points. The distance from the top of the stick to the snow surface is measured using a tape measure at various time intervals and then using the formulae (Figure 3), overall ablation rate can be calculated. Three-time intervals were used in this study; 11:00 and 14:30 on 06/07/17 and 08:30 on 07/07/17. The temperature was also recorded using a thermometer. For this particular study, bamboo sticks were used as they have been found to be more suited to shorter-term studies due to their low cost and low thermal conductivity (Hubbard and Glasser, 2005; Kaser et al., 2003).

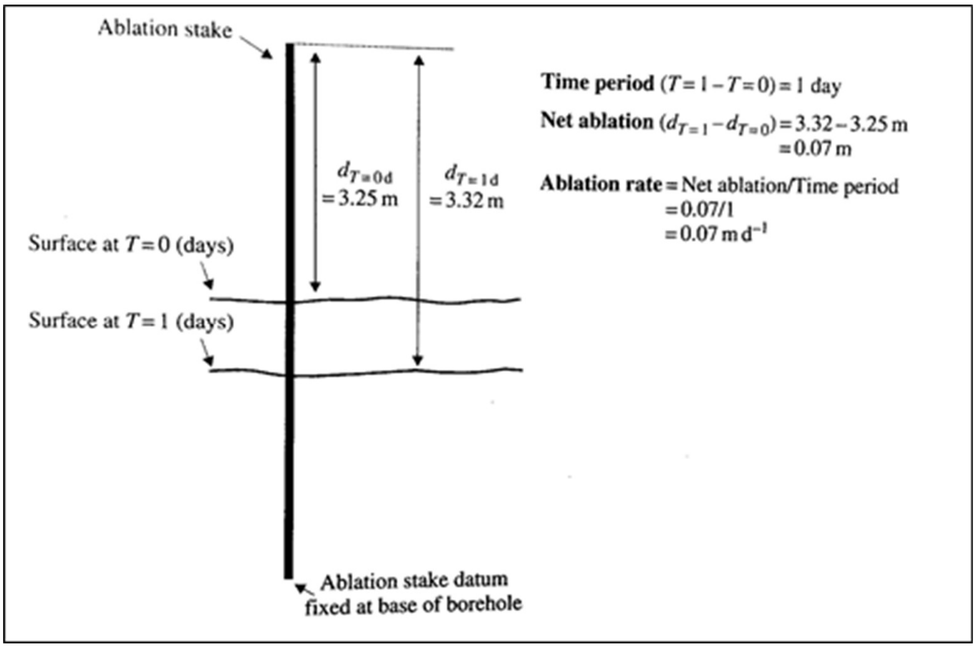

Figure 3- Illustration of the use of ablation stakes to measure surface lowering of snow (Hubbard and Glasser, 2005)

The first hypothesis was addressed by placing mixed clast size debris over an area of 6m^2 on the snowpack, to a depth of 5cm, with 6 ablation stakes randomly distributed across this area. A second, nearby area was left uncovered to enable comparisons to be made.

An extension of the first investigation, 5 stakes were covered by five different sediment sizes (Table 1) to a depth of 5cm and an area of 10cm^2 to further assess the debris' effect on ablation rates.

To study the impact of distance from a blackbody, a 16.65m transect was set up approximately halfway up the snowpack, with 5 ablation stakes at an interval of 4m. Access to the edge of the snowpack was unsafe so the distance between the first stick and the edge was measured (0.65m). The height of each stick was measured using the aforementioned time intervals.

Before carrying out fieldwork, these limitations were considered. Disturbance to the snowpack was highly likely when travelling to and from the ablation stakes; this cannot be eliminated completely, however, this was minimized by walking around the perimeter where possible and setting up a direct path to and from each stick. When using a temperature probe, errors with calibration can arise and in order to prevent this, control measurements were taken before actual measurements.

Due to the nature of completing this study on a field trip, prior to the investigation, there had been 4 days of continuous activity to the snowpack. The specific sites chosen for data collection were located in areas of the snowpack relatively undisturbed.

Table 1. *Sediment types and their associated grain sizes (Glacial flour, sand and gravel clast sizes were approximated; Larger pebbles and cobbles were sorted by direct measurements).*

Sediment type	Grain size
Glacier Flour	150-250 µm
Sands and gravels	1-4mm
Very course pebbles	<5cm b-axis
Fine cobbles	5cm< b-axis < 10cm
Coarse cobbles	10cm< b-axis < 15cm

4.Results

4.1 Hypothesis 1

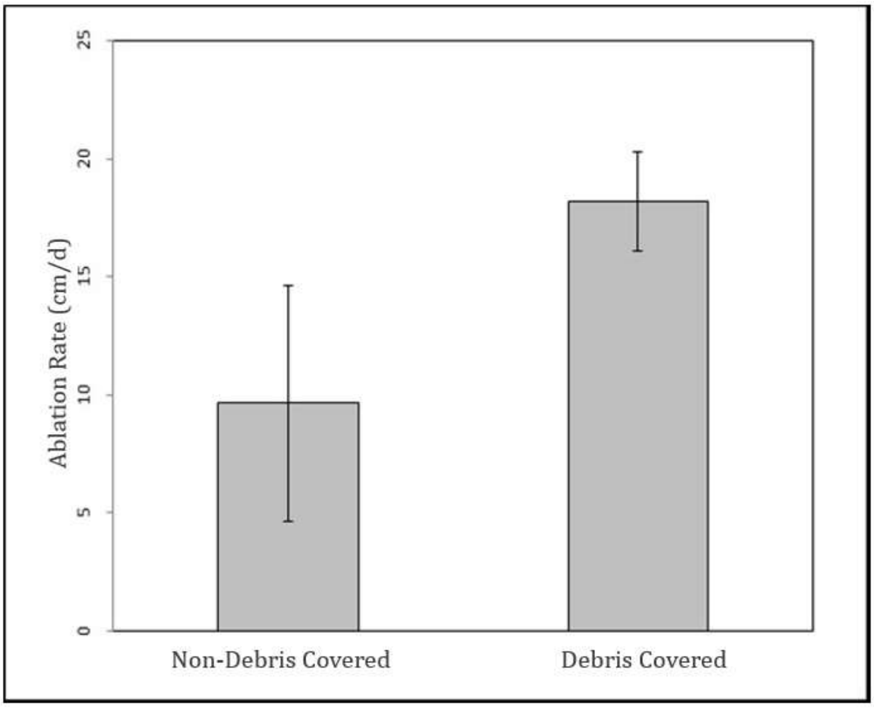

Figure 4- The difference in ablation between debris covered and uncovered snowpacks (± standard deviation)

After removing outliers and carrying out a normality tests on both covered and uncovered areas ($p=0.4098$, $p=0.3655$ respectively), a t-test was carried out which showed statistically significant results ($t=-3.4515$, $df=7.0369$, $p = 0.01058$). Figure 4 shows that the uncovered data had a greater range of results (13.35cm/d) and visually, the debris-covered area appears to have a greater ablation rate (Uncovered mean=9.66cm/d, Debris mean=18.17cm/d).

Table 2. Descriptive Statistics for the debris-covered and uncovered snowpack ablation rates.

	Uncovered Ablation rate (cm/day)	Debris covered ablation rate (cm/day)
Max	16.74	22.01
Min	3.40	15.80
Range	13.35	6.20
Mean	9.66	18.17
Standard Deviation	4.99	2.10
Median	9.60	17.44

4.2 Hypothesis 2

To assess the relationship between grain size and ablation rate, a regression analysis was undertaken; the assumptions were checked, including normality (both variables $p>0.05$) and the relationship obtained was not significant ($p=0.06949$, $r^2=0.6255$). However, by increasing the level of significance to 10%, the data shows a significant negative relationship, with the equation of the regression line being $y=-0.6091x+10.3174$. This relationship indicates that as the grain size increases, there is a decrease in ablation rate.

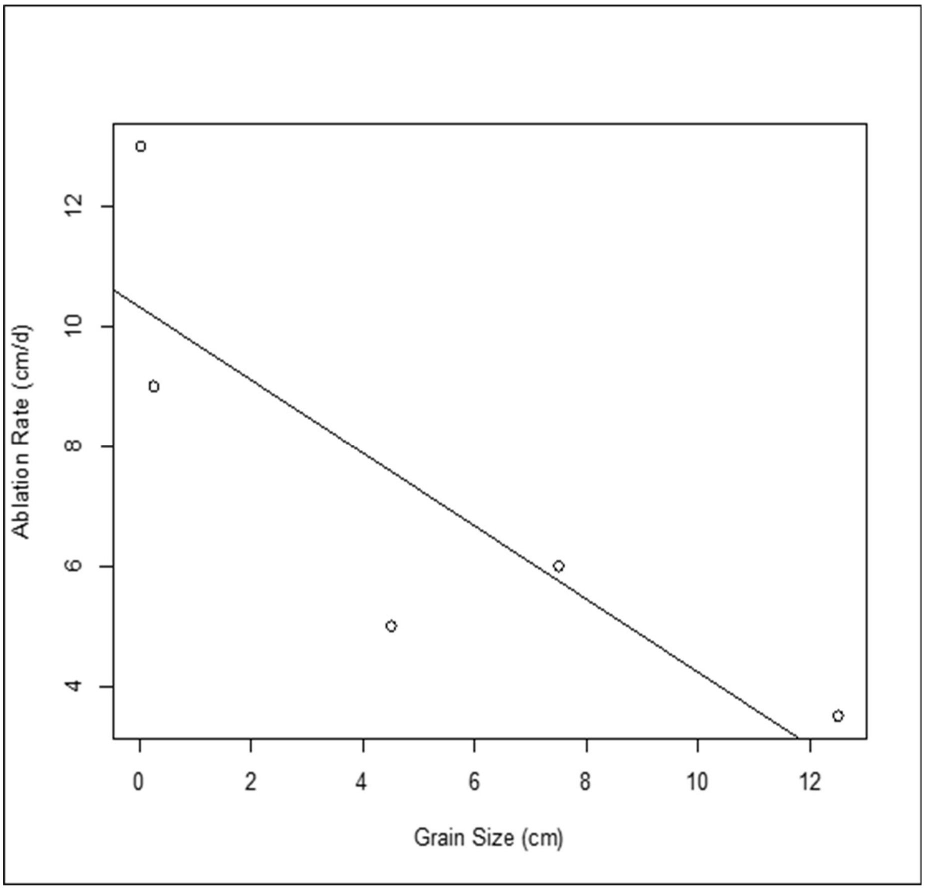

Figure 5 The relationship between grain size (cm) and the ablation rate (cm/day), p=0.06949, r2= 0.6255, y =-0.6091x +10.3174.

4.3 Hypothesis 3

A regression analysis was carried out between the lateral distance from the edge and the measured ablation rate; prior to this, an outlier was removed (distance=8.65m, ablation rate=32.8cm/d) as it biased the data. After checking the assumptions of regression, the analysis was carried out but did not produce significant results (p=0.18, r^2=0.5085). This may be due to the spread of the residuals not showing a linear relationship. However by taking the log of the distance, both the p-value and goodness of fit of the model greatly improved (p=0.0298, r^2=0.9118). This has a strong, negative relationship, demonstrating that the ablation rate may decrease with the log of the lateral distance from the bedrock. This is something that should further be investigated over a larger area to decide if the relationship is in fact logarithmic.

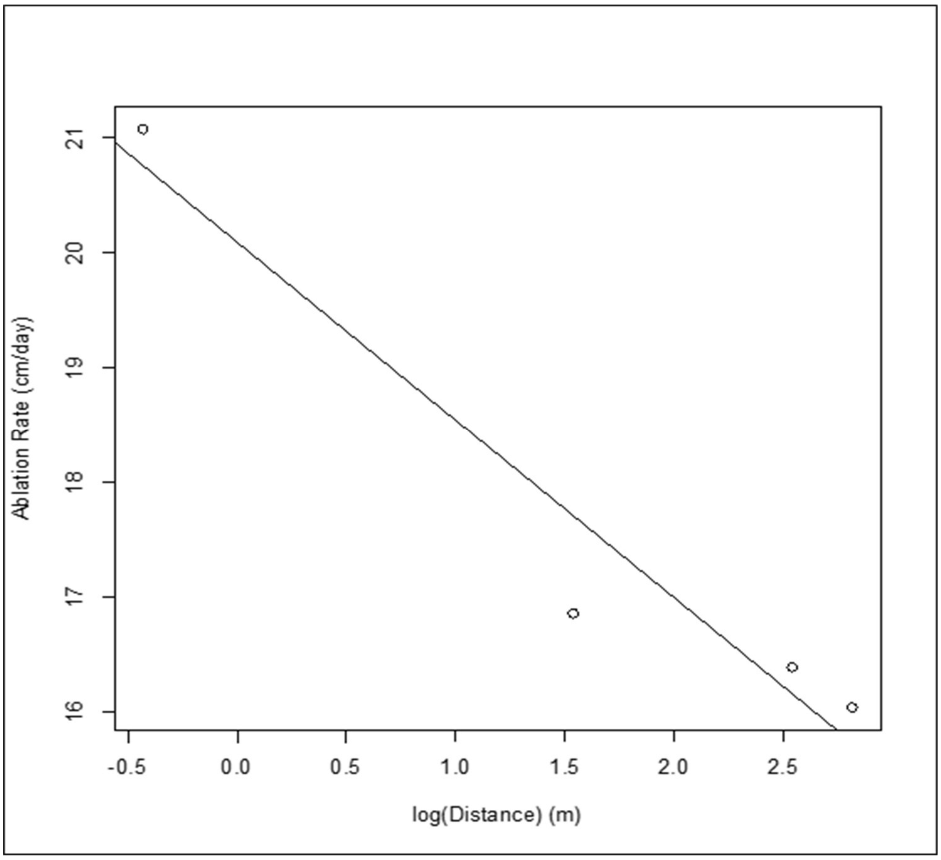

Figure 6 The relationship between the log of the lateral distance from bedrock (m) and the ablation rate (cm/day), p = 0.0298, r2 = 0.9118, y = -1.549x + 20.091

5.Discussion

Although a significant difference was found between debris covered and non-debris covered sites, hypothesis 1 was rejected as the results did not follow the expected pattern found in the literature. The relationship between debris cover and ablation follows a threshold response, with sediment thicknesses greater than the critical value causing reduced resistance between long-wave radiation and the snowpack surface. The generally accepted critical threshold between insulation and enhancing ablation has been found to be around 30mm (Mattson et al., 1993, Takeuchi, Y., Kayastha, R.B. and Nakawo, M., 2000). This has been supported by other studies, for example, Singh (2000) found a thickness of 2mm significantly increased ablation rates. However, these studies focused on glaciers rather than snowpacks, with glacier ice having different physical properties than snowpacks, changing ablation characteristics (Munro, 1990). As such, it is difficult to directly compare our study to existing literature due to the differing properties of snow and ice.

Furthermore, the density of the snowpack was recorded at 513.9 kg $m^{3\ -1}$, lower than the glaciers studied by Singh et al. (2000) which reached 900 kg $m^{3\ -1}$. This is important as Singh et al. (2000) found that debris covered snow experienced greater warming than ice, suggesting that the critical threshold for snowpacks may be higher than for glaciers. The differences in ablation between snowpacks and glaciers, both snow-covered and bare ice, should be considered before conclusions are drawn.

A secondary investigation into the effects of sediment size was carried out. It was hypothesized that finer sediments (glacial flour, sands and gravels, Table 1) if beneath the critical threshold depth would retain and store ground heat and reduced contact the cooler atmospheric temperatures. Larger sediments have larger pore spaces, enabling greater throughflow of cooler, atmospheric air, allowing this heat to escape quickly. Consequently, as the mixed debris generally consisted of mainly finer sediments, the results of this experiment may provide significant context for the results found. However, the relationship between clast size and ablation rate is complex due to multiple interactions with other influencing factors such lithology and density.

For this study, a depth of 5cm was selected because other similar studies, that occurred in environments with the same altitude and alpine conditions, (e.g. Canada and Sweden) used this value (Reznichenko et al., 2010).

The results show critical depth value for this snowpack may be >5cm, hence the debris played the role of a thermal conductor, increasing melt with the finer grain size. A secondary factor was that as it initially melted the surface of the snowpack, it absorbed some of the produced meltwater. This caused the initial colour to change generating a darker colour thus decreasing albedo further likely creating a positive feedback loop.

A further limitation is that this method was only repeated once, therefore many factors such as the albedo, heat flux and heat exchanges from the assorted sediment material and the resultant formation mechanisms (Fujii, 1977) may all have affected the results. It is near impossible to adjudicate between these factors at this time and further investigations into these areas are required.

To address the final hypothesis, it is important to understand the impacts of net radiation. Long-wave radiation has a lower frequency than short-wave radiation and therefore less long-wave energy transfers to the snowpack. However, long-wave radiation acts additionally to shortwave radiation via blackbody radiation from objects surrounding the snowpack, with up to 50% absorption rate compared to only 10% of shortwave. The coupling of long-wave radiation and incoming shortwave radiation causes ablation to occur at a faster rate when compared to only short-wave and over a longer period of time. (McClung and Scharerer, 2006). It is also stated that sensible heat flux and latent heat can further increase ablation figures (Singh et al., 2000) however these were not considered in the study due to equipment and resource limits.

Long-wave radiation from terrestrial sources can heat or cool snow-cover, in this case, the black-bodies from the adjacent bedrock is causing an increase melting effect on the snowpack (McClung and Scharerer, 2006). Long-wave radiation is important in high relief areas, such as the study site, as they drive the ablation by adding more into the radiation receipt (Hubbard and Glasser, 2005).

As shortwave radiation increases, longwave radiation increases linearly. Therefore, ablation should occur greater where the snowpack is located closer to black-bodies (bedrock) than in areas that are not (Singh et al., 2000). This links directly to the final hypothesis because as the distance from the bedrock increases, the ablation decreases. This shows a coupling between long-wave and shortwave radiation close to the bedrock, causing increased ablation, whereas in the centre of the pack there is less impact from terrestrial long-wave radiation and the ablation rate is lower. However, the relationship is not linear suggesting that other factors also were influencing the ablation rates. Further investigation again is needed to this area to constrain the influencing factors.

6.Conclusion

In conclusion, debris cover significantly enhances ablation rates of snowpacks due to the long-wave radiation energy transfer the rocks provide. Further investigations showed that this may be partly due to clast size, as proven by the extension of the first hypothesis. Despite this, the results were not as initially expected, as discussed in section 5.

Overall, the findings of this project can enable a practical understanding of debris-covered glaciers and their relationships with ablation rate. From this, areas of further research can be identified, for example, the possible logarithmic relationship between ablation rates and distance from the black body, as well as the effect of colour and geology. Extensive research can provide necessary measures against the anthropogenic impacts of ablation.

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