Solifluction Lobes on Niwot Ridge: Using Drones, Time-lapse Cameras, and Weather Data to Study Periglacial Features

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Honors thesis submitted to the University of Colorado in partial fulfillment of the requirements to receive honors designation in Geography

April 2018

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Abstract

Solifluction, or gradual mass wasting as a result of freeze-thaw cycles, is a periglacial process that can cause significant changes to landscapes in the margins where glaciers once existed (Draebing and Eichel 2017; Matsuoka 2001). Frost creep is a major mechanism of solifluction in which soils heave in the cold season as the water they contain freezes, causing surface-normal expansion. In the spring thaw, the soil settles in a more vertical direction, producing a net downslope movement (Benedict 1970; Matsuoka 2001).

This study aimed to survey the movement of lobe features created by periglacial processes on Niwot Ridge in order to compare the amount of movement occurring at present to rates measured at the same location in the 1960s by Benedict (1970). Additionally, temperature and precipitation data from the Institute of Arctic and Alpine Research (INSTAAR) was compiled and analyzed due to the relation between these factors and mass movement through solifluction. It was verified that drone imaging and surface modeling software can be used to observe vertical uplift of the surface due to heave. Furthermore, this study shows that time-lapse cameras can be used to provide temperature and visual data on the presence of snow, ice, and water on surface features throughout the inaccessible cold season on Niwot Ridge. The relevance of this data and its comparison with the data from Benedict (1970) is discussed in terms of potential connotations for climate change as well as the feasibility of measurement of landscapes and small-scale mass movement using remote sensing.

Key Words: Solifluction, periglacial, frost creep, frost heave, remote sensing, permafrost, elevation, temperature, precipitation, mass wasting

Introduction

This study puts forth an evaluation of using remote sensing for surveying topographical features and measuring rates of downhill mass movement through the periglacial process of solifluction. Periglacial processes refer to freeze-thaw cycles and their impacts in any location (Anderson and Anderson 2010). Solifluction was originally defined as a flow of water-saturated sediment with reduced internal cohesion under the downward force of gravity that acts upon it (Benedict 1970). More recently, however, this definition was expanded to encompass all mass wasting related to free-thaw cycles, and the previously mentioned definition is now applied to the term gelifluction (Matsuoka 2001). Frost creep is a major type of solifluction since it is a process that moves sediment downslope through freeze-thaw action (Matsuoka 2001). It occurs due to the heaving of soil normal to the surface as the water it contains freezes into ice lenses, and then settles in a more vertical direction downslope as it thaws (Benedict 1970). Frost creep is further split into diurnal frost creep through daily, rapid freeze-thaw action and annual frost creep through gradual freezing and heaving throughout a cold season and subsequent thaw in spring (Matsuoka 2001). It is typically difficult to differentiate exactly how much of any observed downslope movement on solifluction lobes is caused by gelifluction as opposed to annual frost creep, so measured downslope movement is attributed to solifluction as a whole and the heaving component of frost creep is noted as well (Matsuoka 2001).

This study used photogrammetry, or the use of photography to map physical features, to measure the impacts of these periglacial processes on land features in the vegetated alpine zone of Niwot Ridge, which is a long term ecological research area in the Front Range of the Colorado Rocky Mountains near the town of Nederland. Benedict (1970) measured rates of mass movement manually at multiple sites on Niwot Ridge between 1962 and 1967 and compared these to rates from the distant past, noting that motion through solifluction had declined significantly on most areas of Niwot Ridge since the end of the Middle Stade of the Pinedale Glaciation about 12,000 years ago.

The extent that solifluction causes mass movement is dependent in part upon climate-related factors such as soil moisture availability, vegetation cover, and the presence of permafrost, so changes in the rates of erosion through these processes over time may be indicative of changes in climatic conditions. Benedict (1970) noted the relationship between climate change and solifluction by using radiocarbon dating to show that movement is slower now than it was in the past; he thought climate change explained this change because it led to less precipitation on Niwot Ridge. Less precipitation means less moisture inputs, thus this result of changing climate conditions led to less moisture content in soil which in turn would mean less solifluction could occur (Benedict 1970). INSTAAR has been collecting temperature data since the early 1950's and precipitation data since the early 1960's for Niwot Ridge, and this facilitates an evaluation of whether observed changes in the amount of mass movement occurring through solifluction show any relation to changes in seasonal weather conditions between Benedict's study period and the present. This study aimed to use drone imaging and time-lapse cameras to model the structure and movement of some of the same solifluction lobes that Benedict (1970) measured in order to compare past and present impacts of this periglacial process as well as to evaluate the effectiveness of drone photogrammetry in observing small-scale mass movement in comparison to manual measurement techniques.

Description of the Study Area

Niwot Ridge is an established research area in the Front Range of the Colorado Rockies that is focused on the study of an alpine ecosystem that extends from subalpine coniferous forests to alpine tundra at higher elevations.

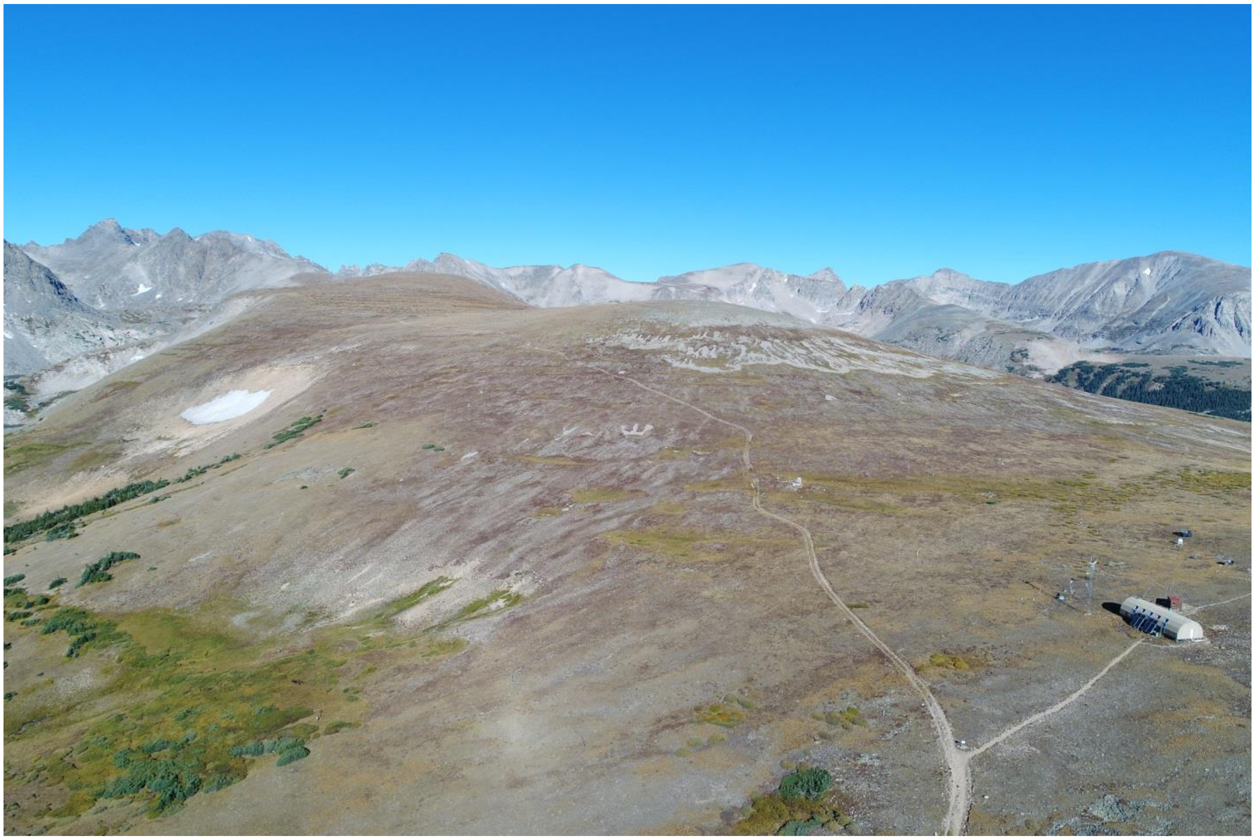

Figure 1: An overview of the upper part of the Niwot Ridge LTER which is the focus of this study. The tundra lab is visible on the saddle on the bottom right of the image, all of the features studied are either on the slope just above it (to the West) or below it to the left (the South slope). Photo taken by Rachel Glade on 9/22/17.

Figure 1 illustrates that this long term ecological research area encompasses a wide range of features including a cirque glacier and various glacial landforms like moraines. There are lakes in its valleys, and talus slopes, patterned ground, and permafrost on the upper slope of the ridge. Niwot Ridge serves as an ideal measurement site for studies in numerous fields of natural science since it is considered to be representative of the Southern Rockies as a whole (Benedict 1970). Moreover, a significant amount of data and research pertaining to the area is available, which gives further context to understanding the climatic conditions and geomorphological changes that exist in the area. It is an active, accessible research site that has been minimally disturbed by researchers and thus its natural character remains intact enough to facilitate measurements that ought to reflect the conditions of the overall Southern Rocky Mountain area.

The specific measurement sites that were surveyed on Niwot Ridge were located near the tundra lab, which is above treeline in the alpine zone. This is an area in which there is sparse vegetation—mainly low-lying grasses and shrubs. Plant growth in this area depends on the establishment of significant snowpack that remains throughout the winter to act as a water source as it thaws in the spring (Benedict 1970). While the overall area has fairly limited vegetation due to intense wind and weather events as well as extreme temperatures, variations in physical features like topography and slope aspect create small scale pockets called microenvironments with differing conditions (Benedict 1970). The alpine zone of Niwot Ridge stays fairly cold throughout the year—for context, the average air temperature for the year of 2017 was about -3 ◦C at the D-1 station, which is located on the upper part of the ridge at an altitude of about 3750 meters—and temperatures can get as low as -40 ◦C in the winter months (Losleben 2018).

Benedict's Lobe 45 was the main site that was measured in this study. Its location is on the South-facing slope just below the tundra lab in a relatively flat area on a saddle surrounded by steep slopes on almost all sides, so it is a collection point for runoff during the spring thaw and as a result it is typically more highly saturated with water compared to the rest of Niwot Ridge. This means it is more likely to still be exhibiting movement from solifluction than other, less saturated areas (Benedict 1970; Matsuoka 2001). Additionally, it is often exposed throughout the winter since a lot of snow can be blown away by the intense winds that are characteristic of unprotected alpine areas. This means that there is little insulation of the soil so ground temperatures at Lobe 45 are lower than the surrounding area as a result (Benedict 1970). Its elevation is roughly 3480 meters according to Benedict (1970); our remote GPS device reported 3500 meters. I also looked at other sites on the West slope above the tundra lab heading up towards the D-1 weather station, which was also used in this study. Soil motion measurement sites were established on a turf-banked lobe (henceforth referred to as Lobe T) and a stone-banked lobe (Lobe S) in this area, but there is little moisture observed in the soil of these areas so significant mass movement by solifluction is unlikely (Benedict 1970). Lobe S's elevation is roughly 3585 meters and Lobe T is at about 3551 meters according to our remote GPS device. The final measurement site was a turf-banked lobe that Benedict named Lobe 499. It is located at about 3400 meters elevation on the North side of the West slope heading up to D-1. This site was highly disturbed by Benedict when he trenched it at the end of his study to get a soil profile, but a measurement site was still established to see how disturbance affects rates of movement.

Dynamics of Periglacial Processes on Niwot Ridge

It is important to note that areas that have higher levels of soil moisture will exhibit higher rates of movement due to solifluction than hot and dry locations since this type of mass movement is limited by the amount of water present in the soil (Benedict 1970). Water lessens the cohesion between soil particles, and when soil on a slope is saturated with moisture it can slide slowly downward (Benedict 1970). These areas of material that are saturated in water and exhibit a greater flow moving downslope due to solifluction form bulging landforms called lobes over and adjacent to material that is not moving

(Benedict 1970). Turf-banked lobes, exemplified by Figure 2, are bordered with vegetation and develop from periods of significant solifluction underneath areas with a lot of plant cover, whereas stone-banked lobes form as frost creep sorts coarser grains together into strips of larger rocks that border fine grained soil layers (Benedict 1970). The degree that these lobes move downslope through solifluction depends on multiple factors; the meteorological and hydrological conditions of a given area, the grain and pore size of the media, the presence and type of vegetation cover, local topography, slope steepness, surface load, and the presence of an underlying layer of permafrost all play a part in determining the extent that this periglacial process will impact a landscape (Benedict 1970; Draebing and Eichel 2017; Anderson and Anderson 2010).

Figure 2: A turf-banked lobe (Lobe 45) that is the major feature being analyzed in this study. Photo taken by Rachel Glade with a DJI Phantom 4 Pro Drone on 9/22/17. Note people for scale in image.

As noted, climatic factors such as temperature and precipitation have a major impact on the amount of movement caused by solifluction since soil moisture largely depends upon these factors (Benedict 1970; Anderson and Anderson 2010). Both gelifluction and the heaving of soil that is observed in frost creep are favored by saturated conditions and by slow, deep freezing of water into ice lenses during the cold season

(Benedict 1970). Ice lenses typically form parallel to the surface and perpendicular to heat flow in fine grained sediments during the cold season (Anderson and Anderson 2010). Capillarity movement of water in soil due to surface tension allows the water to migrate from higher temperature areas to the lower temperature freezing zones where lenses form even against gravity, and it is this collective formation of ice lenses along with the volumetric expansion of freezing water that cause soils to heave (Anderson and Anderson 2010). As a result, the moisture content of the soil determines how much heaving (and thus creep) can occur since ice lenses cannot form without adequate water supplies. This is clearly related to how much moisture is input by precipitation and how much is lost by evaporation or sublimation. Similarly, significant gelifluction occurs only in areas where the water table remains high enough during the fall freeze to permit thick ice-lens development, which lessens soil cohesion and facilitates flow during thaw (Benedict 1970). If, for instance, climate change was causing a decline in precipitation in the area then there may not be enough moisture input into the soil before the cold season to facilitate the formation of the ice lenses in the soil that allows solifluction to occur. These considerations seem to indicate that the current state of temperature and precipitation conditions in the area plays a deciding role in the amount of mass movement by solifluction observed.

The extent of the effects of solifluction as a general process is not a simple function of soil moisture content, however, there are multiple factors at play; a significant one is the presence of permafrost (Benedict 1970). Underlying layers of permafrost, or soil that remains below 0 ◦C for at least two years, promote soil saturation by acting as an impermeable layer that impedes the percolation of water so that it must instead remain closer to the surface and eventually flow downslope (Benedict 1970). However, rising temperatures have led to an absence of permafrost below altitudes of about 3700 meters on Niwot Ridge except for in some North and East facing slopes (Leopold et al 2015). As a result, the degree of mass wasting caused by solifluction on Niwot Ridge specifically has declined notably so that this process is only really active in areas that remain wet through fall and into the cold season. That is, active, measurable solifluction on Niwot Ridge and other areas where permafrost is now absent is only possible in locations that retain enough moisture through autumn so that they can form ice lenses in the cold season that inhibit drainage and generate the critical pore water pressure that is needed for this process to occur (Draebing and Eichel 2017). This means that mass movement through solifluction on Niwot Ridge in particular is restricted by the spatial availability of soil moisture to areas where topographical features like divots and shallow ponds channel water flows and collect wind-blown snow (Draebing and Eichel 2017; Leopold et al 2015). Thus, it is important to consider that a rise in temperatures in this area could not only evaporate away significant amount of soil moisture, it could also cause permafrost to melt as well as prevent its reestablishment (Leopold et al 2015). Reduced soil moisture and the absence of an impermeable layer to impede water percolation would strongly limit the flow of soil by solifluction (Benedict 1970).

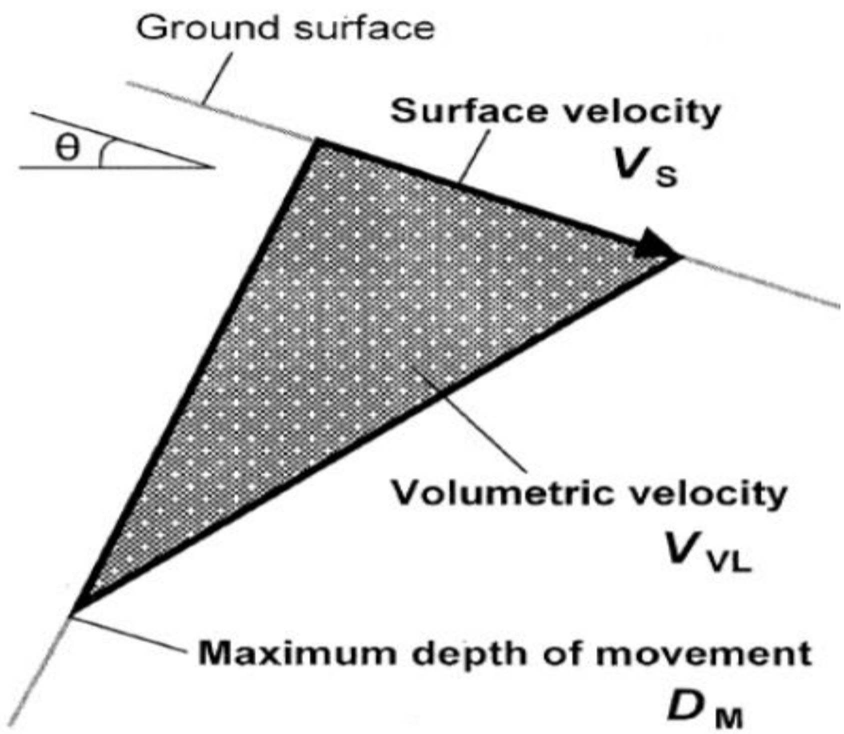

Figure 3: A diagram of the components of solifluction, which is reflected by the V_{VL} that comes from multiplying V_S by D_M (Matsuoka 2001).

A study done by Matsuoka (2001) that primarily utilized data on solifluction from mountainous regions of the Northern Hemisphere found that areas with more temperature fluctuations will have more rapid freeze-thaw cycles and exhibit more movement through diurnal frost creep as a result, whereas areas with consistently lower temperatures throughout the cold season would exhibit more deep motion through annual frost creep and gelifluction. Warmer temperatures lead to higher surface velocities and more frost heave because there are more freeze thaw cycles occurring (Matsuoka 2001). Conversely, cooler temperatures lead to higher volumetric velocity (surface velocity * maximum depth of movement, see Figure 3 above) and gelifluction because there is more soil cohesion, which leads to a greater maximum depth of movement (Matsuoka 2001). Furthermore, cooler temperatures and increased precipitation typically allow for increased vegetation growth, and the presence of more vegetation is associated with a greater depth of movement (Eichel et al 2017). Again, a greater depth of movement means a higher volumetric velocity and thus a higher rate of mass movement due to gelifluction and annual frost creep (Matsuoka 2001). As a result, it is important to know whether the temperature and amount of precipitation being observed on Niwot Ridge in the present is different from the quantities observed in Benedict's study years. This facilitates a comparison of differences in the amount of movement postulated by theory and the displacement values produced by direct measurements of these processes. Moreover, it is important to determine how this study's measurements of solifluction, and air temperature using remote sensing compare with the manual measurements in Benedict (1970), the temperature and precipitation data collected by INSTAAR, and the expectations that come with the relationships noted in Matsuoka (2001) and Eichel et al (2017).

Solifluction Measurements of the Past

Comparing recent and past surveys of local changes in processes like solifluction is important to understanding the changing geomorphology of local landscapes, especially when changes in solifluction have potentially significant connotations for the phenomenon of climate change. Such a comparison was accomplished in this study by revisiting sites on Niwot Ridge that were mapped and monitored by Benedict (1970) during the period of 1964 to 1967 in order to see any differences in rates of solifluction that may exist now that 50 years have gone by. Benedict's survey of solifluction found that his one of his main turf-banked lobes (Lobe 45) moved 9.4 mm/yr on average between 1965 and 1967 (Benedict 1970). The most movement he observed was on the turf-banked lobe that he named Lobe 499, which moved 17 mm/yr (Benedict 1970). His stone-banked lobes moved around 3 mm/yr (Benedict 1970). Benedict noted that the majority of movement through solifluction that has been occurring on Niwot Ridge since the latest Pinedale and earliest Neoglacial ice advances (about 10,000 years ago) was through frost creep since sorted strips and stone-banked lobes have become more prevalent, but overall solifluction was not found to be highly effective in the present other than in particular microenvironments that are saturated with water in the fall (Benedict 1970). This study revisited his sites on Niwot Ridge to measure current rates.

Methods

Images of Lobe 45 taken from above using a DJI Phantom 4 Pro quad-drone with a standard 1" CMOS camera comprised the main remote sensing data used in this study. We collected imagery in the fall (September 22, 2017) and winter (March 17, 2018). Multiple, partially overlapping images of Lobe 45 were taken from different points above the lobe so that they could be later compiled to create a single image that encompassed the entire lobe. The Phantom 4 uses a barometric altimeter that records elevation readings of the area captured in the images so that they can be used to make Digital Surface Models (DSMs) that show surface topography of the landscape being sensed. Altitudes relative to the ground level that the Phantom 4 takes off from are measured by first capturing an image at ground level just after takeoff to use as a reference. The Phantom 4's main flight mode, which is called positioning mode, employs onboard GPS and barometric altimeter systems automatically stabilize the drone when it is not moved manually so that a fairly constant altitude is maintained barring impacts from wind.

Images of Lobe 45 were captured in fall 2017 on September 22nd as a reference to compare surface elevations against images of the lobe taken in late winter of 2018 on March 17th. The fall images were captured at an average altitude of about 30 meters above ground level (AGL), while the winter images were taken at an average altitude of 18 meter AGL since the windier conditions on that day required a lower flying height to be safe. It was necessary to plan out flight days in advance since the Phantom 4 can only handle a maximum wind speed of 22 mph, and for safety it is better to aim for even calmer conditions. For reference, the wind speed during the March 17th flight was only about 4 mph on average, however the frequent and often intense gusts that are characteristic of Niwot Ridge and most high altitude locations are always a factor to be considered. It was necessary to capture more images in the winter in order to compile a full view of Lobe 45 since the images were taken at a lower altitude which meant that each single image covered less area.

Figure 4: .tif image (left) and DSM (right) of Lobe 45 taken by the Phantom 4 on 9/22/17 and compiled using Maps Made Easy software. Lighter color on the DSM indicates higher values for elevation.

Once the images of Lobe 45 from the fall and winter were captured using the Phantom 4, the numerous, partially overlapping pictures were combined to make a full-view .tif image and a DSM (see Figure 4 above) for each day using a software called Maps Made Easy. These images were then imported into QGIS so that profiles of elevation values across Lobe 45 before and during the cold season could be drawn and compared. This was accomplished by overlaying the .tif images from each measurement day above their corresponding DSM layers in QGIS and then selecting profiles on the DSMs between features that are visible in the images from both dates. The elevation values of the same horizontal transects were observed across time by using the profile tool in the program to place a starting and ending point on the same two features across the lobe in both the fall and winter DSMs (see Figure 5 below). Visibility issues from snow cover in the winter image and elevation discrepancies in the winter DSM due to heaving of the few consistently noticeable start and end points were determining factors in the profiles that could be selected. Once the profiles were selected in QGIS, a table of values for elevation and latitude/longitude coordinates for points along the line became available to export into Excel. The latitude/longitude coordinates of the starting and ending points along profiles drawn on the image of Lobe 45 in QGIS could be used to find the corresponding ground distance between the two sets of coordinates by using the haversine formula. This distance was compared with the manually measured length of one of the transects that this study established on Lobe 45 as well as with a distance computed from the same image in another software called ImageJ that is discussed below.

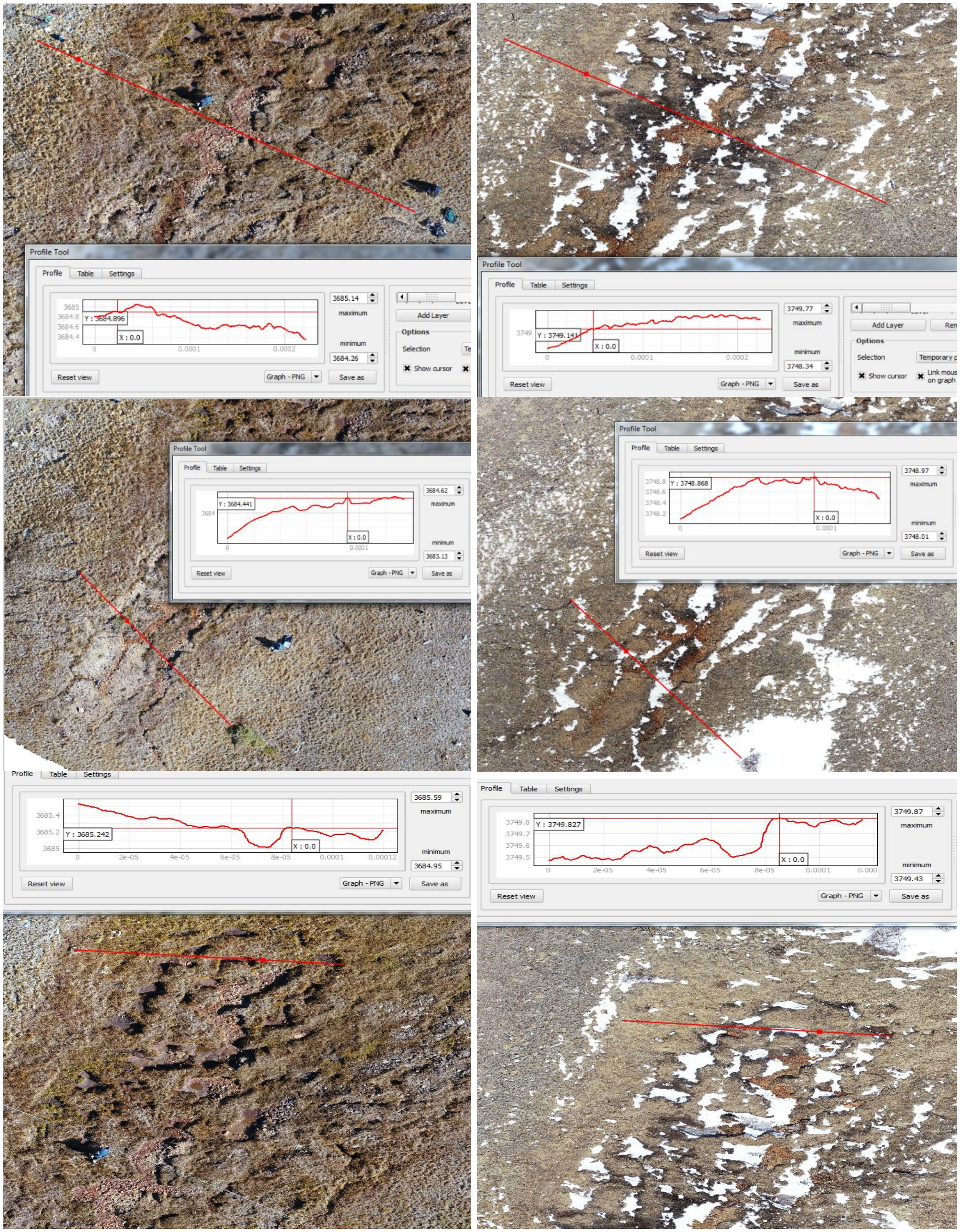

Figure 5: Images of profiles drawn in QGIS on the left are from 9/22/17, images on the right are from 3/17/18. The center area and downslope, or East side (the right side of the images here) shows noticeable heaving in all of the profiles, which is to be expected since this is where most moisture is channeled and collected. The first pair is termed Profile 1, the second pair is Profile 2, and the third is Profile 3.

Graphs of elevation values along each profile across Lobe 45 from both the fall and winter images were made in Excel by subtracting the elevation value of the starting point of each profile from all points along the corresponding profile in order to produce a picture of altitudes across the lobe in fall and winter relative to the same starting point. This subtraction was necessary since the original elevation values in the DSMs are given in what appears to be an attempt at the drone reporting true elevation in meters above sea level using its barometric altimeter. These "true" values were off from one another by an unrealistic 100 meters and the values for both the fall and winter DSMs (about 3680 meters and 3750 meters respectively) were far above the actual elevation of Lobe 45 recorded by GPS, which is about 3500 meters. Nonetheless, the presence of visible dips in the profiles in QGIS that correspond to ponds on the lobe show that the drone accurately reads relative elevations, so this was highlighted by the graphs shown below in Figures 6, 7 and 8.

The images of Lobe 45 from the Phantom 4 were further analyzed using ImageJ software, which allowed for measurement of distances and lengths of features on the lobe. This was accomplished by importing .jpeg versions of images of Lobe 45 from the fall and winter and then setting a real-distance scale in the image based on a known length of an object in the images. In this case, the same white drone box with a known side length of 0.381 meters was set out to be visible in the images taken on both 9/22/17 and 3/17/18. A line was drawn along this side of the box in both images within ImageJ, and once a scale was set based on this known length it became possible to measure distances in the image since a distance/pixel ratio was now set in the software. These distances were compared with both the length of a transect we measured manually using a tape-measurer and the distance of the same transect computed using the latitude/longitude coordinates taken from the images through QGIS in order to evaluate the effectiveness of using Phantom 4 images with different software to measure distances.

A stationary Moultrie Game Camera was also set up facing Lobe 45 on 9/22/17 to provide time-lapse images of the lobe surface. It captured images at 3 hour intervals starting at 9:45 am on 9/22/17 up until 11:49 pm on 12/14/17. The Moultrie Cam also records air temperature values at the time that each image is captured. This set-up facilitated the compilation of a record of surface conditions and air temperature on Lobe 45 throughout a significant part of the cold season. The record of conditions on Lobe 45 over time was made by logging the air temperature and whether the major ponds on the lobe were dry, wet, or covered with snow or ice for the images taken at about 12:45 pm each day.

Downhill displacement of solifluction lobes was intended to be the main phenomenon that was measured manually at the outset of this study. Measurement was attempted by establishing rebar benchmarks on both sides of the lobes being measured and stretching a string horizontally level across the benchmarks and over the lobes as a reference line for position at the start of the study. The string was fitted onto the downslope side of the rebar. Benchmarks were hammered down into xeric locations outside of the lobes using a sledgehammer until they were securely in the ground. Lines of nail markers were placed directly below the string by visually lining up the center of the nail head with the overlying string. The nails were inserted so that only about 2 cm of the nail remained above ground; the length of these nails was specifically chosen since displacement from solifluction occurs mainly in the upper 25 cm of soil (Benedict 1970).

The nails were labeled sequentially with letters starting at A for the leftmost nail of each lobe. Downhill displacement of the lobes was measured in reference to the stationary benchmarks by looking at how far the center of the nail head moved away from the string. 4 lobes were surveyed using 1-2 lines of 4-10 15.3 cm long nails.

The measurement apparatus on Lobe 45 was established on 7/10/17 for the lower line and 9/22/17 for the upper line. Benchmarks were placed 5.5 meters (m) apart on the lower line with 4 nails placed every 1 m in between starting at 1.5 m past the benchmark. The benchmarks on the upper line were 20.2 m across with 10 nails placed every 2 m in between starting at 1 m past the benchmark. One set of benchmarks were established at Lobe S on 6/26/17. They were 2.6 m apart with 6 nails placed every 30 cm in between. Two sets of benchmarks were established at Lobe T on 6/26/17; the upper transect was 4.4 m across and the lower benchmarks were 4.8 m apart. 6 nails were placed underneath the upper transect of Lobe T at 40 cm intervals and 7 nails were established under the lower transect also at 40 cm intervals. Finally, benchmarks were established 4.5 m apart at Lobe 499 on 7/10/17 and 6 nails were placed below at half meter intervals.

Eight total temperature probes, or ibuttons, were established at 5 different locations around Lobe 45 to record soil temperatures on site at hourly intervals. Three of the locations have two high resolution ibuttons each, one at 2 cm depth and one at 10 cm depth. The last two sites each have one low resolution ibutton placed at a 1 cm depth. Furthermore, soil temperatures were measured at each nail of Lobe S and Lobe T, as well as the transects established on Lobes 45 and 499, using a handheld temperature probe during the initial establishment and the later measurement visits. The probe was inserted into the soil to the full length of the probe, which was a depth of about 3 cm.

INSTAAR temperature data from the D-1 weather station from 1952-2016 and precipitation data from 1964-2016 was compiled and analyzed to discern climate patterns. INSTAAR records data on temperature and precipitation at multiple locations on Niwot Ridge for the sake of ecological research. The D-1 station has the longest record at the site (established in 1952 for temperature and 1964 for precipitation) and it reports daily average values calculated from hourly averages of 720 samples taken every 5 seconds (Losleben 2018). This is the only record in the area that goes back far enough to offer a consistent report of conditions spanning from the years studied in Benedict (1970) to the present, so the past and present values for temperature and precipitation at D-1 were used to facilitate a comparison of weather conditions between the two time periods. The average daily temperatures given in the INSTAAR data for D-1 were further averaged into average temperatures per year with standard deviations (σ) for each year during the study period of Benedict (1970) from 1962 to 1967 as well as for 2011 to 2017, which were the most recent years for which INSTAAR data was available. These values were used to make line graphs of mean annual temperatures for each time period. Minimum and maximum temperatures for each year in the earlier and modern time periods were also logged in order to see if temperature fluctuations have become more extreme. Total precipitation quantities for each water year (from October 1st to September 30th) in 1965-1973 and 2012-2017 time ranges were also logged, averaged, and graphed.

Results

The relative elevations for Profile 1 that were created using the fall and winter DSMs show significant heave occurring in the middle and the East, downslope side of the center part of Lobe 45 (Figure 6). The maximum heave of a surface point on this profile appears to be about a meter or even more according to this method.

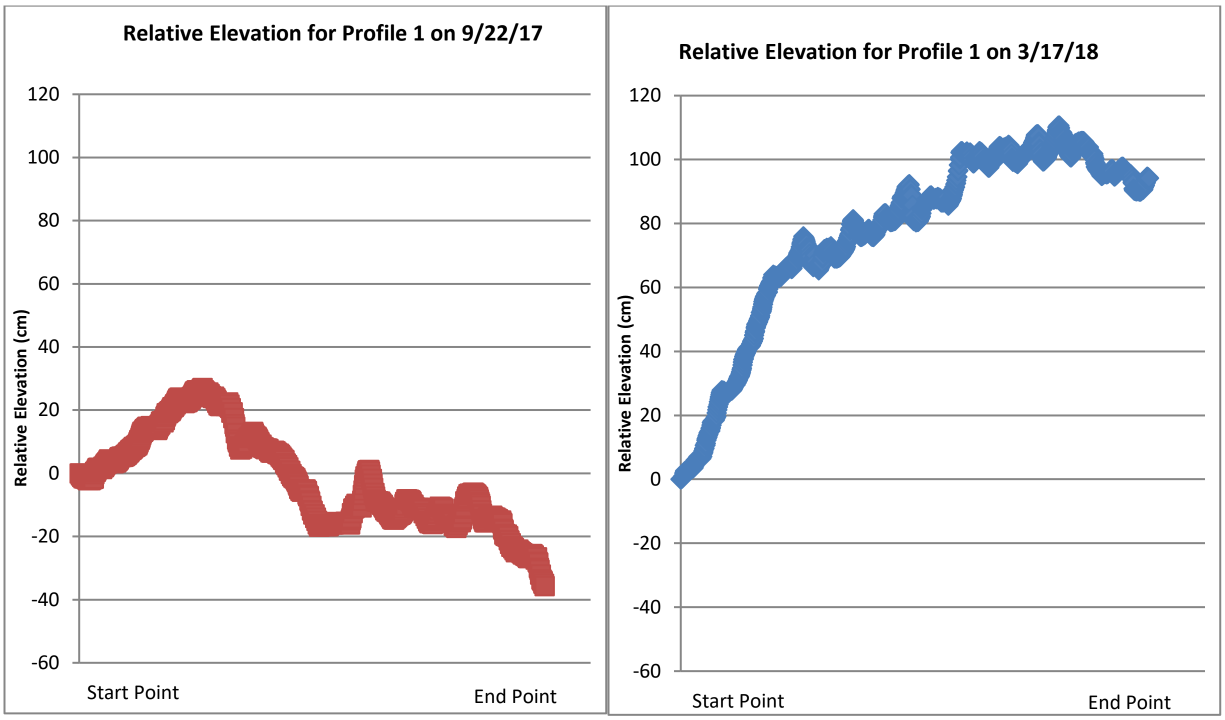

Figure 6: Graphs of relative elevation for Profile 1, located across the middle section of Lobe 45. Comparing the fall and winter values for surface elevation relative to the same starting point using this method indicates that by March 17th this section of Lobe 45 had heaved up to a meter above its surface elevation on September 22nd.

Relative elevation changes for Profile 2 were the opposite (Figure 7), with the elevation values relative to the starting point in the DSM being higher in the fall than they were in the winter for this transect at the foot of Lobe 45. This result is probably due to an issue with heaving of the starting point along with the rest of this profile which creates the appearance of a smaller relative difference in elevation along this section of the lobe.

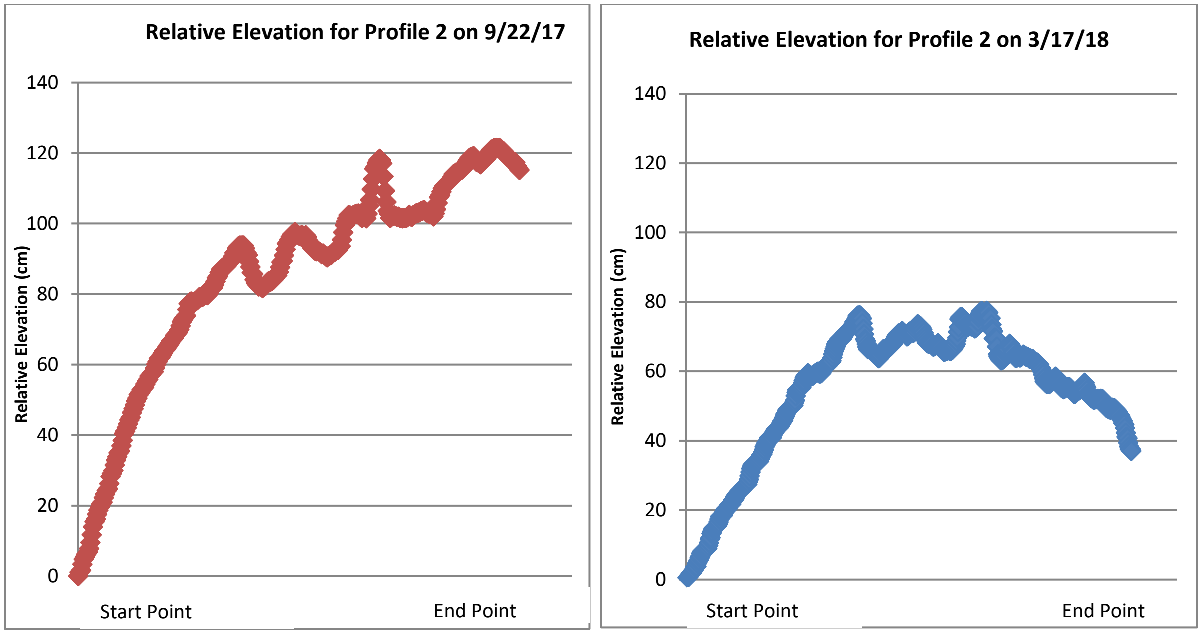

Figure 7: Graphs of the fall and winter relative elevations for Profile 2, which goes across the foot of Lobe 45. The comparison of these two graphs seems to indicate the lobe settled and was lower in surface elevation on March 17th, however in reality this was likely the result of heaving of the starting point used in the profile that acted to reduce the difference in elevations between the starting point and the rest of the profile.

The relative elevations found in reference to the starting points on Profile 3 showed notable heaving in the winter along this transect of the head of Lobe 45 (Figure 8). Additionally, the distinct dip in this profile corresponds to a pond on the surface of the lobe that the profile was drawn over in QGIS, indicating that the Phantom 4 is capturing a record of surface topography that is at least representative even if its elevation readings are not exact.

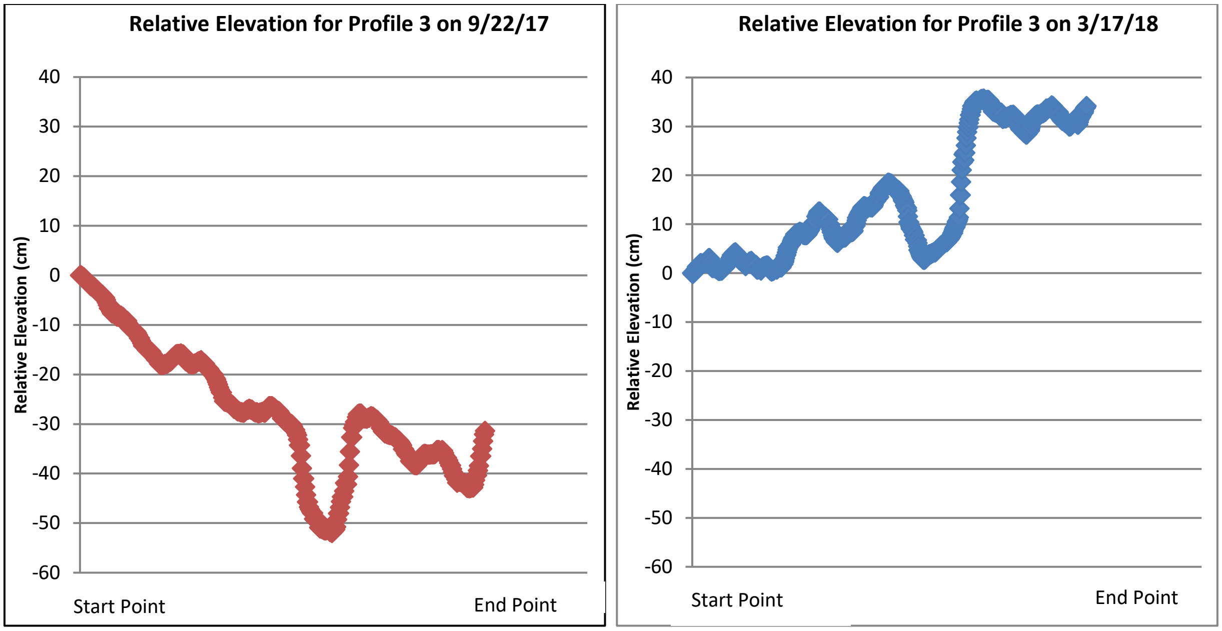

Figure 8: Graphs of the fall and winter relative elevations of Profile 3, located at the head of Lobe 45, which show a notable dip that corresponds to a pond on the lobe surface and also indicates a heave of up 70 cm at this location between Septermber 22nd and March 17th.

The distance between the two rebar benchmarks of the upper transect that was established on Lobe 45 was measured to be 20.2 meters with a tape measurer. A similar distance of 20.14 meters was found by converting the latitude/longitude coordinates of the start and end points of a line drawn over the same transect between the same two benchmarks that were visible in the .tif image of Lobe 45 in QGIS, indicating that the drone recorded coordinates for positions on the ground accurately. The distance of this same transect was measured a third time in ImageJ by setting a scale using a known object in a .jpeg image of Lobe 45 and drawing a line between the same two benchmarks. This method produced a value of 21.35 meters.

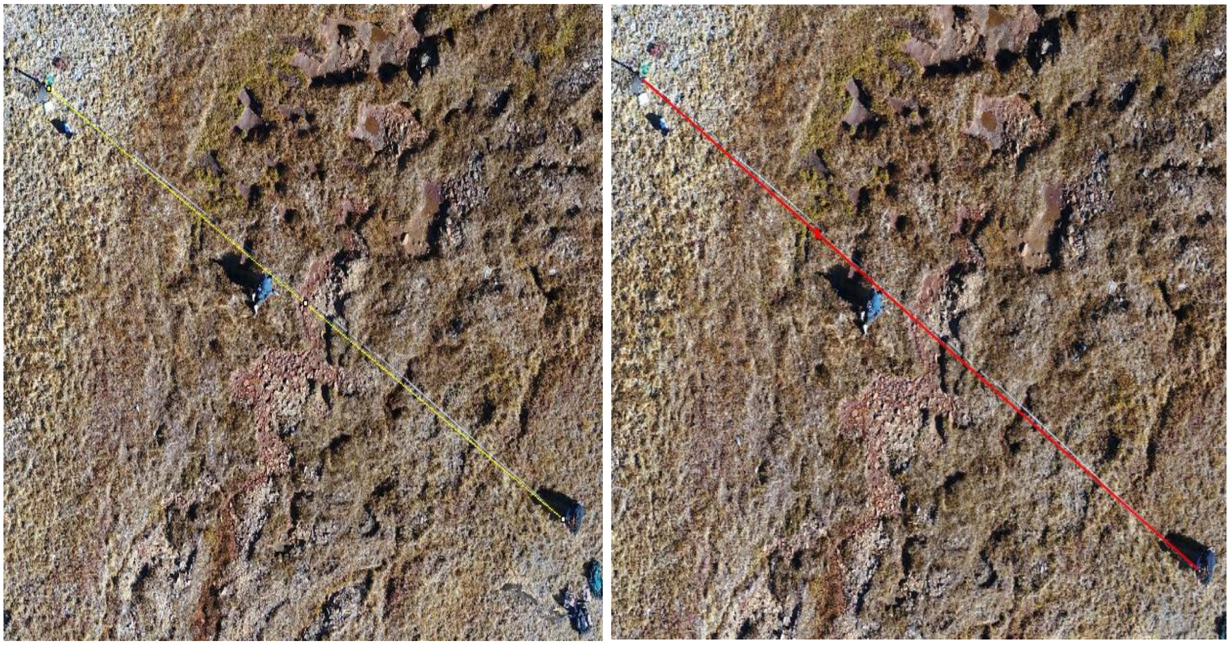

Figure 9: Images of lines drawn across Lobe 45 in ImageJ on the left and QGIS on the right in order to take and compare measurements of distance across the lobe to the known distance of this transect (20.2 meters) that was measured by hand using a tape-measurer on 9/22/17.

The information gleaned from the images captured by the Moultrie Cam between 9/22/17 and 12/14/17 were compiled into a record of air temperature and presence or absence of water, snow, or ice on Lobe 45 at about 12:45 pm for each day that had clear images (Table 1). The ponds visible on the lobe surface, which had been water-filled in the summer, were dry on 9/22/17 when the time-lapse camera was set up. Out of the 75 days for which images were available, only the first day had dry conditions on the lobe. Five days had wet conditions, meaning that snow had fallen and then melted to fill up the shallow ponds on the lobe with water; all of these days were in September. 34 days, or 45.3% of the total, had snow cover; these were fairly evenly spaced throughout the observation period. The remaining 35 days, or 46.7%, showed ice cover in the ponds; these were also evenly spaced out but only started after mid-October when temperatures began staying closer to or below 0 ◦C.

Table 1. Air temperature and pond conditions on Lobe 45.

Date	Temp (◦C)	Cover Type	Date	Temp (◦C)	Cover Type	Date	Temp (◦C)	Cover Type	Date	Temp (◦C)	Cover Type
9/22/17	14	dry	10/11/17	15	snow	10/30/17	-4	snow	11/18/17	-2	ice
9/23/17	4	wet	10/12/17	11	snow	10/31/17	2	ice	11/19/17	0	ice
9/24/17	4	snow	10/13/17	0	snow	11/1/17	7	ice	11/20/17	-2	snow
9/25/17	22	snow	10/14/17	6	snow	11/2/17	6	ice	11/21/17	0	ice
9/26/17	22	snow	10/15/17	4	ice	11/3/17	1	snow	11/22/17	0	ice
9/27/17	4	wet	10/16/17	10	ice	11/4/17	-2	snow	11/23/17	2	ice
9/28/17	10	wet	10/17/17	16	ice	11/5/17	5	snow	11/24/17	1	ice
9/29/17	18	wet	10/18/17	11	ice	11/6/17	1	snow	11/25/17	7	ice
9/30/17	11	wet	10/19/17	12	ice	11/7/17	6	snow	11/26/17	10	ice
10/1/17	11	snow	10/20/17	-6	snow	11/8/17	4	snow	11/27/17	13	ice
10/2/17	15	snow	10/21/17	2	ice	11/9/17	7	snow	11/28/17	2	ice
10/3/17	17	snow	10/22/17	4	ice	11/10/17	0	ice	11/29/17	2	ice
10/4/17	18	snow	10/23/17	6	ice	11/11/17	2	ice	11/30/17	1	ice
10/5/17	7	snow	10/24/17	14	ice	11/12/17	6	ice	12/1/17	3	ice
10/6/17	2	snow	10/25/17	-3	ice	11/13/17	5	ice	12/2/17	4	ice
10/7/17	15	snow	10/26/17	-1	snow	11/14/17	3	ice	12/3/17	-10	snow
10/8/17	-3	snow	10/27/17	0	snow	11/15/17	7	ice	12/4/17	-5	snow
10/9/17	16	snow	10/28/17	6	ice	11/16/17	-2	snow	12/14/17	-5	snow
10/10/17	12	snow	10/29/17	3	ice	11/17/17	-6	snow			

The manual measurement of downslope movement of nail lines due to solifluction did not produce any usable results for this study. Significant movement through solifluction begins to occur along with the spring thaw, so the results will only begin to be measurable in late April or early May (Benedict 1970). Moreover, this study did not employ the use of a theodolite to ensure that the nails were directly below the string that marked the starting positions for the transect being studied so parallax when attempting to visually place markers and observe movement became an issue. It should also be noted that Lobe T, Lobe S, and Lobe 499 were all still buried in snow on the final day of field research on 3/17/18, so they would not be measurable until early summer regardless.

Mean values for annual air temperature at D-1 (Table 2 and Figure 10) in the span of time from 2011 to 2017 ranged from -2.6 to -7.1 ◦C, whereas the mean annual air temperatures (MAATs) in Benedict's study period from 1962 to 1967, ranged from -2.0 to -4.3 ◦C (Losleben 2018). Only 2013 and 2017 had MAATs that were not lower (-3.9 ◦C and -2.6 ◦C respectively) than the MAATs in the years studied in Benedict (1970) (Losleben 2018). 2012 and 2014-2016 were notably colder with MAATs at -6 ◦C or lower (Losleben 2018). It should also be noted that the minimum temperatures were mostly lower and the maximum temperatures were mostly higher from 2011-2017 than they were from 1962-1967, indicating a developing trend towards more extreme fluctuations in temperature (Losleben 2018; McGuire et al 2012). Along with this, all of the recent years had larger standard deviations around the annual means, which would seem to indicate more variation in temperature throughout the year. The average value for soil temperature at all of the locations recorded up until 9/22/17 using the handheld temperature probe was about 10 °C, so soil temperatures were slightly higher than the air temperatures on Niwot

Ridge during the summer of 2017, which averaged out to around 8 ◦C. Soil temperature records for this study remain incomplete as the ibuttons that were established to measure temperature over time were frozen fast to the ground, thus this data can only be recovered after the thaw.

Table 2. Mean annual air temperature data from D-1, selected years.

Year	D1 Mean Temperature ± σ (◦C)	D1 Max Temperature (◦C)	D1 Min Temperature (◦C)
1962	-2.6 ± 8.7	16	-41
1963	-2.0 ± 9.3	17	-36
1964	-4.3 ± 9.4	17	-27
1965	-3.5 ± 8.1	15	-28
1966	-2.9 ± 9.4	18	-30
1967	-3.5 ± 8.6	17	-32
2011	-4.5 ± 10.1	19	-35
2012	-6.1 ± 10.0	17	-40
2013	-3.9 ± 12.2	21	-34
2014	-7.0 ± 9.5	14	-32
2015	-6.1 ± 10.1	15	-30
2016	-7.1 ± 10.0	15	-33
2017	-2.6 ± 8.8	19	-24

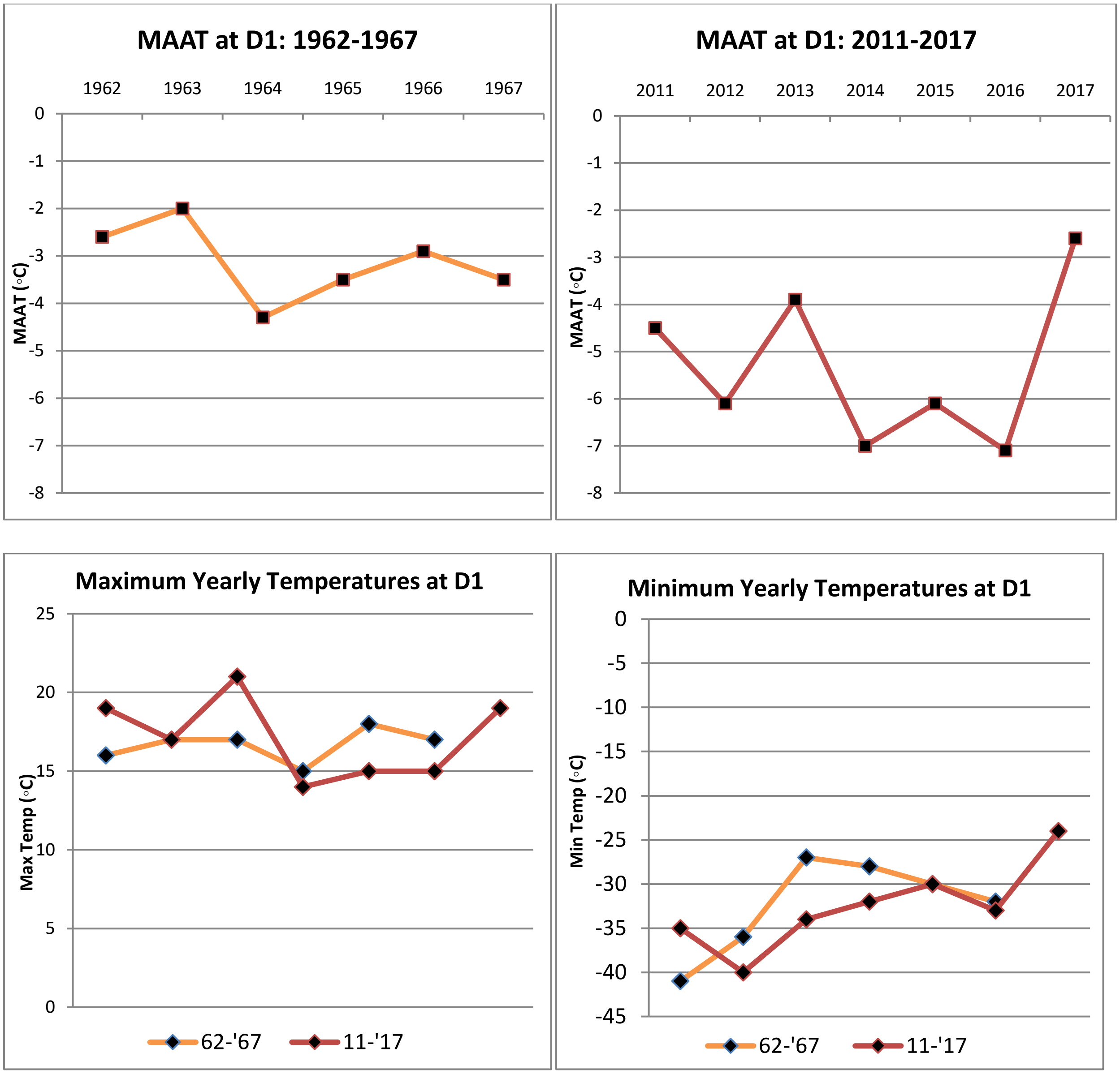

Figure 10: Graphs of MAAT, yearly maximum, and yearly minimum temperatures for D1 compiled from the INSTAAR data recorded at that station during the years studied in Benedict (1970) juxtaposed with the values from the last 6 years. The MAAT graphs illustrate a trend of decreasing average temperatures at D-1 over time, whereas the graphs of yearly minimum and maximum temperatures show a trend towards more extreme highs and lows for temperature at D-1 in the present.

Table 3. Precipitation data from D-1, selected years.

Water Year	Total Precipitation (mm)	Water Year	Total Precipitation (mm)
1965	1403	2012	1032
1966	984	2013	1303
1967	1586	2014	1115
1968	841	2015	1349
1969	976	2016	1118
1970	938	2017	1274
1971	894		
1972	982		

’65-’72 Average: 1075.5 mm/yr

’12-’17 Average: 1198.5 mm/yr

Analysis of the INSTAAR data on precipitation at D1 (Table 3 and Figure 11) shows that overall there was more total annual precipitation incident upon Niwot Ridge in the water years from 2012 to 2017 than there was in the period of 1965 to 1972 (Losleben 2018). While both the 1965 and 1967 water years had higher total precipitation values than any of the years in the 2012-2017 range, averaging the yearly totals from both ranges of time showed that the more recent years had about 120 mm more precipitation per year on average (Losleben 2018). Moreover, Kitter et al (2015) calculated a trend of increasing precipitation over time at a rate of 60 mm/yr/decade at Niwot Ridge. This means that with each decade that goes by the total amount of precipitation that falls on Niwot Ridge each year goes up by about 60 mm. Precipitation amounts can vary significantly from year to year due to phenomena like the El Nino Southern Oscillation, but beyond these natural cycles there is a general trend of rising amounts of precipitation on Niwot Ridge overall as time progresses.

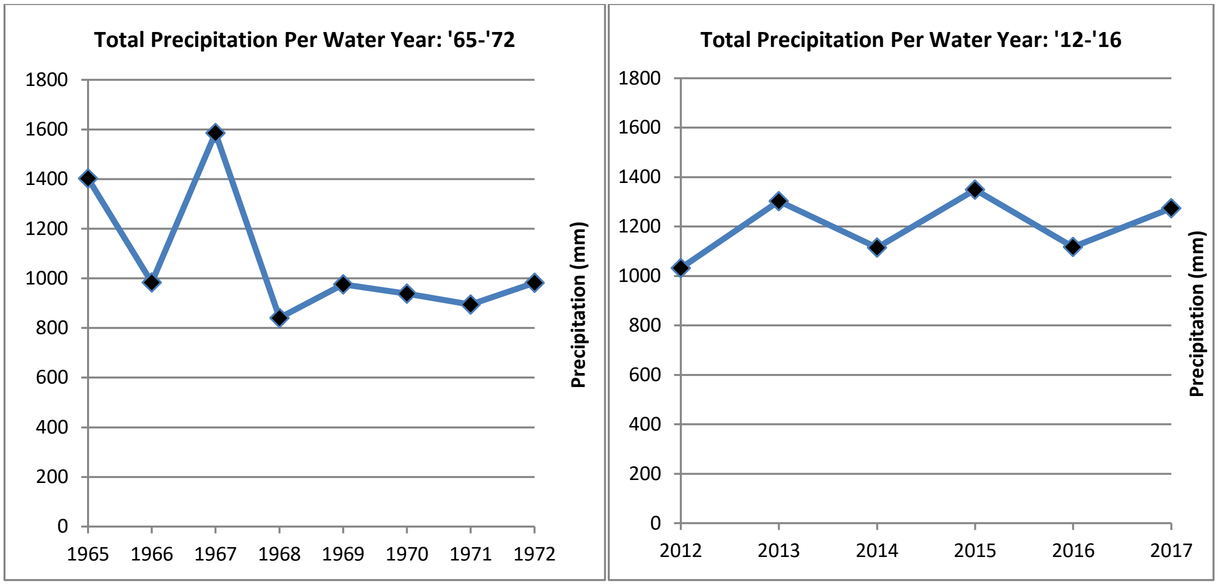

Figure 11: Graphs of the total annual precipitation for the water years of 1965-1972 and 2012-2017, which show an increase in precipitation at D1 in the present relative to the past.

Discussion

While the Phantom 4 has definitely proven to be able to create DSMs that are representative of the surface topography, neither the original elevation values that came with the DSMs from Maps Made Easy nor the values calculated relative to the starting points of each profile seemed to be accurate. Profile 1 appeared to have heaved about a meter or more according to the DSMs produced in this study, however the maximum value for heave of the surface of Lobe 45 found by Benedict (1970) in just about the same location was only about 36 cm. For further reference, the maximum heave found in the review of solifluction studies given in Matsuoka (2001) was just 18.5 cm and most of the others were below 10 cm. The Moultrie Cam record and the INSTAAR weather data indicate favorable conditions for frost heave to occur on Lobe 45 during this study period, and a larger supply of water to the soil from increased precipitation inputs could indeed facilitate more heave in the present than there was in Benedict's study period, but an increase in heave on the order of 60 cm is highly unlikely. Nonetheless, it was clear that significant heave did occur on Lobe 45 since some of the ibutton temperature probes, which were inserted centimeters below the surface in the fall, had risen to be visible above the surface by March 17th. As a result, it is likely the case that the heave shown in the DSMs from the Phantom 4 is real, just exaggerated due to the relative inaccuracy of the readings from its barometric altimeter (DJI 2018).

Performing manual and remote measurements of frost heave at the same location in order to compare values and check the Phantom 4 for accuracy would be an interesting avenue for further study of the use of drone photogrammetry in monitoring periglacial processes. In addition, more accurate values and better comparisons of surface dynamics could be captured with drone photogrammetry in future studies of solifluction by improving upon the methods of this experiment. This could be accomplished by establishing better benchmarks, ensuring that reference images are taken after takeoff every time the a measurement flight is begun, and making an effort to capture images from the same flying height before and after so that the images will have ground sampling distances that are similar if not the same. This would help in picking out the same profiles in both images in order to maximize comparability.

The Phantom 4 provides a platform to capture images at a much finer spatial resolution than most of the readily available images that are produced by Earth-observation satellites. For instance, Landsat-8, a widely used platform for Earth-observation satellite imagery, has a spatial resolution of 30 meters in the visible spectrum, whereas the Phantom 4 has a spatial resolution of 3 cm per pixel for images taken at 70 meters above ground level (DJI 2018; USGS 2018). This value gets even smaller if images are captured closer to the ground, for instance the spatial resolution was 8 mm per pixel for the fall images of Lobe 45 which were taken at 30 m AGL and about 5 mm per pixel for the winter images, taken at about 18 m AGL. Moreover, using a drone to capture images facilitates an ability to focus in on specific features of any size more easily based on the user's discretion since it is directly piloted by the user. These factors are very important when trying to pick out consistent features in before and after images that are smaller in size, such as the benchmarks and ponds on Lobe 45 that were used in this study.

A tradeoff to using the images from the standard sensor on the Phantom 4 is that it has a limited spectral resolution in comparison to a sensor like Landsat's Enhanced Thematic Mapper (ETM). The standard CMOS camera on the Phantom 4 only allows for sensing in the visible wavelengths, whereas the ETM and many other Earth Observation sensors can sense in near-infrared (NIR) and even thermal wavelengths as well (DJI 2018; USGS 2018). NIR and thermal sensing are both valuable for mapping soil moisture content and structure since they can penetrate below the surface, and this information is relevant to the distribution of occurrence of solifluction (USGS 2018). It is possible to include a supplemental thermal sensor mounted onto the Phantom 4 platform—this could be a potential next step for further research into the dynamics of solifluction on Niwot Ridge.

The results of the observations of the Moultrie Cam imaging that spanned from 9/22/17 to 12/14/17 are valuable in that they present a fairly long term record of the conditions on Lobe 45 in a season that is often too intense for human field research. These records confirmed that significant amounts of moisture were deposited onto the lobe during this time period—the fact that virtually every day on this record showed the presence of water on Lobe 45 in liquid or solid form is evidence that there is enough moisture in the soil there to facilitate the formation of the ice lenses that drive solifluction. Furthermore, these types of records are also useful for biological studies on Niwot Ridge since the presence or absence of liquid water and snow cover is important for microbial life in the area. The temperature records from the Moultrie Cam had some problems such as reporting 65,000 ◦C temperatures and showing values that were inconsistent with the INSTAAR data at times, but the values were not totally inaccurate and were useful as supplemental information about the daily conditions that were impacting the type of surface cover (snow, ice, water, or dry) observed on Lobe 45. It was also a useful record of how temperatures were fluctuating throughout each day since the camera captured eight pictures a day that showed the temperature at each time.

The INSTAAR data show a trend of decreasing average temperatures and increasing average precipitation at D-1 on Niwot Ridge (Losleben 2018). This coupled with the relationships that Matsuoka (2001) and Eichel et al (2017) described raises an expectation that there would be more gelifluction occurring now than there was in the past since temperatures are decreasing, precipitation is increasing, and this means that more gelifluction and frost creep should be observed in theory. However, the permafrost below 3700 meters that was reported on Niwot Ridge in the 1970s is all but gone in the present, so freeze-thaw action and ice lense development are necessary for solifluction to occur on Lobe 45 in the present (Leopold et al 2015). Temperatures are decreasing in the winter, but they are also increasing in the summer and this precludes the reestablishment of permafrost which requires soil to remain below 0° Celsius for at least two years (Leopold et al 2015). As noted previously, an absence of permafrost means there is not impermeable layer to inhibit water percolation, which in turn means that solifluction may not increase despite the decline in cold season temperatures (Benedict 1970). Moreover, gelifluction becomes more prominent along with seasonal thawing, so the timeline of this study precluded any observations of major downslope mass movement through this process (Matsuoka 2001). Nonetheless, the Moultrie Cam record confirmed fairly high inputs of moisture from precipitation onto Lobe 45 during the 2017-2018 cold season and the Phantom 4 photogrammetry confirmed that significant heave occurred on parts of the lobe from between September 2017 and March 2018. In addition, Leopold et al (2015) noted that recent surveys of Lobe 45 showed that it was still moving about 1.1 cm per year in 2013. Thus, it is expected that downslope mass movement due to solifluction would be observed on Lobe 45 if a survey was performed in early May 2018 after the spring thaw (Matsuoka 2001).

The findings of this study are relevant in multiple areas. Increased precipitation and decreased temperatures in the cold season likely means that there will be more snowpack development that will feed into a higher amount of discharge in the spring. It will be important to be aware of this increased amount of water so that it can be managed for optimal use as summer temperatures continue to rise. Further studies would be needed to determine the direction of flow and distribution of the increased discharge. Furthermore, increased amounts of solifluction will gradually wear away high elevation slopes and cause habitat and landscape changes that ought to be studied. Increased solifluction and turf-banked lobe development also creates different microenvironments that alter the types of plants that will be found in the area (Draebing and Eichel 2017). If Lobe 45 remains active the disturbance caused by solifluction promotes the establishment of ecosystem engineering plants like *Dryas octopetala* that are movement resistant and limits the establishment of post-successional plants such as *Salix hastata* that require stability (Draebing and Eichel 2017; Eichel et al 2017).

Another important takeaway of this study comes from the compilation of the INSTAAR temperature records for D-1. As mentioned previously, this analysis and comparison of temperatures at D-1 over time showed a trend toward more extreme fluctuations between seasons, with maximum temperatures being mostly higher and minimum temperatures mostly lower in the 2011-2017 time period as opposed to those recorded from 1962-1967 (Losleben 2018). Moreover, the standard deviations around the MAATs produced for both time periods were higher in the recent years than they were in the earlier ones, and this likely indicates a greater spread of temperatures throughout the year at D-1 in modern time. This is consistent with the widely acknowledged assessment of the way that climate change is impacting the world, which is a tendency towards exacerbating extremes in weather (NASA 2017). As a result, this study helps exemplify that the INSTAAR temperature data for D-1 most likely supports the notion that climate change is a real and measurable catalyst of more extreme changes in weather. The only reason to say most likely instead of definitely is that the higher standard deviations observed in the 2011-2017 time period may be in part due to a larger amount of missing values for average daily temperatures in the INSTAAR record for these years since they have not been filled in using extrapolation of supplementary records yet (Losleben 2018). Averages that come from smaller sample sizes typically exhibit relatively larger values for standard deviations, so this could be a source of error in the climate assessment made above.

There are some other sources of error that must be considered for this study. Measurement error from visual assessment of movement is one main consideration, for lining up the nail heads with the overlying string can be problematic on highly windy days which are common at this high elevation location. The timing of the field work had to be planned in advance so that measurements could be during calm periods of relatively calmer days in order to minimize error from visual parallax.

An additional source of error for the both the manual measurements and the drone photogrammetry may have been that the rebar benchmarks were not stabilized with cement the way that they were in Benedict (1970) so they may have moved a little along with the ground they were placed in due to heave. This would impact the readings of frost heave of the lobe because if the reference point that the rest of the lobe surface was compared to raised upward in elevation itself then this would make it seem as though less heaving occurred than what actually happened. The benchmarks this study established and used for both manual and remote measurement of heave were placed about two meters off the side of the lobe in seemingly xeric locations, but the profiles produced from the drone photogrammetry indicate that they still heaved. Any further studies of a similar nature should either move the benchmarks even farther off lobe to even drier areas that are highly unlikely to heave or to emulate Benedict and secure them with cement.

The error in the measurement of distance on Lobe 45 using ImageJ to analyze .jpeg images from the drone should also be considered because this method could be a useful way to measure downhill displacement if the methods used in this study were improved upon. The main reason that this method of measuring distance produced a value that was about a meter off of the true value was that the object with known dimensions that were used to set the scale in the software was small enough that it was hard to select the exact size of the feature without being off by some amount of pixels, which equate to a few millimeters of error in the scale depending on the spatial resolution of the image. If a larger, easier to measure object was used to set a more accurate scale, then this technique could be used to measure more than simple distances. This method of spatial analysis could be used to measure downslope mass movement if markers that were more clearly visible in the drone images were placed on the lobe and clearly visible benchmarks were placed in a grid around the lobe and stabilized as noted above. If this set up was established then distances from benchmarks to markers could be measured and compared in images from before and after the annual freeze and thaw to view displacement.

Future studies could use the capabilities and limitations outlined in this experiment in the use of drone photogrammetry to produce better maps and models of features and their movement using remote sensing. For example, if objects that were large and distinct enough to be picked out in the drone images were used as markers in the transects established on the lobe instead of nails then it would be possible to measure downslope displacement as well as vertical heave using the photogrammetry techniques from this study. Furthermore, if a thermal camera was added to the drone platform then this would make it possible to map soil moisture across wide areas of Niwot Ridge and similar study sites for periglacial processes that depend in part upon water supply to the soil. This would help to predict where movement will occur due to solifluction using remote sensing.

Conclusion

This study has shown that drone photogrammetry facilitates modeling of changes in landscape due to periglacial processes and has the potential to be used to measure and make comparisons of vertical displacement of the surface due to frost heave. Further potential for measurement of downslope mass movement through solifluction using software to analyze distances has been noted as well. Analysis of INSTAAR weather data for the D-1 station on Niwot Ridge showed that temperature has decreased on average between the time of Benedict's 1962-1967 study and the present (Losleben 2018). More specifically, the trend shows more extreme heat in summers and more extreme cold in winters (Losleben 2018; McGuire et al. 2012). Precipitation at D-1 has increased on average between Benedict's time and the present (Losleben 2018; Kittel et al. 2015). Manual measurement of downslope movement was limited due to persisting snow cover, however a return trip in early May to make measurements would likely report movement on Lobe 45 of a similar amount to the rate of about 1 cm/yr reported in both Benedict (1970) and Leopold et al (2015). Lobe 45 remains an active site for solifluction because its soil has enough to facilitate development of the ice lenses that drive this process in the absence of an underlying layer of permafrost (Leopold et al 2015). Moreover, the overall trend of decreasing temperatures and increasing precipitation observed on Niwot Ridge should promote a continuation and potential increase in mass wasting through gelifluction and annual frost creep (Losleben 2018; Matsuoka 2001). Finally, the temperature data analysis performed in this study serve as a probable confirmation of the tendency towards increasingly extreme weather patterns as a result of climate change (Losleben 2018; NASA 2017).

Acknowledgements

I would like to thank my wonderful advisors, Suzanne and Bob Anderson, and our amazing drone pilot, Rachel Glade, so much all of their help, I could not have asked for a

better research team and I had a great time studying, hiking, and mammoth watching with you all on Niwot Ridge! I'd also like to thank Bill Travis for being on my committee and helping me to take this step towards my future in geosciences. Finally, I want to thank Katherine and Frank Baxter and everyone who is involved in the Von Dreden Fellowship for helping to support my project.

Works Cited

Anderson R, Anderson S. (2010): "Periglacial Processes and Forms." *Geomorphology: The Mechanics and Chemistry of Landscapes* (270-303). Cambridge, UK: Cambridge University Press.

Benedict, J. (1970): "Downslope Soil Movement in a Colorado Alpine Region: Rates, Processes, and Climatic Significance." *Arctic and Alpine Research* 2, no. 3: 165-266.

"Climate change evidence: How do we know?" NASA (August 2017). https://climate.nasa.gov/evidence/.

Draebing D, Eichel J. (2017): "Spatial Controls of Turf-Banked Solifluction Lobes and Their Role for Paraglacial Adjustment in Glacier Forelands." *Permafrost and Periglacial Processes*, 28: 446–459. DOI: 10.1002/ppp.1930.

Eichel J, Draebing D, Klingbeil L, Wieland M, Eling C, Schmidtlein S, Kuhlmann H, Dikau R. (2017): "Solifluction meets vegetation: the role of biogeomorphic feedbacks for turf-banked solifluction lobe development." *Earth Surface Processes and Landforms*, 42: 1623–1635. DOI: 10.1002/esp.4102.

Kittel T, Williams M, Chowanski K, Hartman M, Ackerman T, Losleben M, Blanken P. (2015): "Contrasting long-term alpine and subalpine precipitation trends in a mid-latitude

North American mountain system, Colorado Front Range." *Plant Ecology & Diversity*, 8:5-6, 607-624. DOI: 10.1080/17550874.2016.1143536.

Leopold M, Lewis G, Dethier D, Caine N, Williams M. (2015): "Cryosphere: ice on Niwot Ridge and in the Green Lakes Valley, Colorado Front Range." *Plant Ecology & Diversity*, 8:5-6, 625-638. DOI: 10.1080/17550874.2014.992489

Losleben, Mark. (2018): "Air temperature data for D1 chart recorder from 1952-10-1 to ongoing, daily." http://niwot.colorado.edu

Losleben, Mark. (2018): "Precipitation data for D1 chart recorder from 1964-10-1 to ongoing, daily". http://niwot.colorado.edu

Matsuoka, Norikazu. (2001): "Solifluction rates, processes and landforms: a global review." *Earth-Science Reviews*, 55: 107–134.

McGuire CR, Nufio CR, Bowers MD, Guralnick RP. (2012): "Elevation-Dependent Temperature Trends in the Rocky Mountain Front Range: Changes over a 56- and 20-Year Record." *PLoS ONE,* 7(9): e44370. https://doi.org/10.1371/journal.pone.0044370

"Phantom 4 Pro Specs," DJI (2018). https://www.dji.com/phantom-4-pro/info

"What are the band designations for Landsat." USGS (March 2018). https://landsat.usgs.gov/what-are-band-designations-landsat-satellites

Software used: QGIS, Maps Made Easy, ImageJ