UAV-derived imagery permits quantification of ice volume loss on tropical, high altitude glacier

By:

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Under the Supervision of Dr. Julie Bartley

Abstract-

Glaciers in the tropical Andes, like those worldwide, are experiencing rapid ice volume loss due to climate change. Tropical areas are of significant interest in glacial studies because they are especially sensitive to climate change since they experience minimal seasonal temperature variation. In addition, glacier meltwater in many tropical areas is important for downstream human use. Past studies have demonstrated that ice surface area is shrinking, but determining the volume loss rates gives three-dimensional information about glacier response to climate change and permits evaluation of hydrological effects. In this study we determined ice volume loss for a debris covered section of the Reschreiter Glacier on Volcán Chimborazo in Ecuador. Traditional geodetic approaches of measuring ice volume change, including the use of satellite-derived digital elevation models and airborne LIDAR, are difficult due to the small size of Chimborazo's glaciers, frequently cloudy conditions, and limited local resources. Instead, we obtained imagery with an Unmanned Aerial Vehicle (UAV) and processed this imagery using Structure from Motion photogrammetry to create a Digital Elevation Model to compute ice volume loss. The Reschreiter Glacier experienced an ice volume loss of 790,000m^3 ±172,000m^3 from June 2012 to June 2017. Various surface features, such as ice cliffs and proximity of ice to exposed bedrock, are contributing to ice volume loss while the debris covered nature of the glacier helps to insulate the glacier and decrease rates of melting compared to a clean ice face on the surface of the glacier.

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Introduction-

With average global temperatures on the rise, glaciers in mountain ranges throughout the world are experiencing increased ice retreat. One area in particular that is experiencing the full effect of this increase in temperature is the Andes Mountains in South America, which account for >99% of all tropical glaciers in the world (Chevallier et. al., 2011). With warming, there is potential for an increase in ice-cap and glacier collapse as well as an increase in mass wasting in the Andes (Bradley et. al., 2009). Volcán Chimborazo is just one of the many glacier-covered mountains within the Andes Mountain that has glaciers on it shrinking due to the effects of climate change. Temperature and solar radiation play a significant role in this. There is minimal variation in average temperatures throughout the year in this area. As temperatures continue to increase because of climate change, the yearly average will continue to rise and temperatures will on average be high enough to allow for melting on the surface of the glacier. There is also minimal year-round variation in solar radiation in the tropical Andes (Rabatel, et. al. 2013).

One glacier in particular that is experiencing melt is the debris-covered, detached portion of the Reschreiter Glacier. The meltwater that comes from glaciers is very important for the agricultural communities surrounding the mountain as well as being a crucial source for other domestic use (Immerzeel et. al., 2014;). In the past, the Reschreiter Glacier has been a reservoir of water that has been available from the surrounding communities. As the Reschreiter Glacier and other glaciers on the mountain continue to melt, the reservoir of water will continue to decrease and will no longer be able to provide the communities with the water they once had. It is important to understand the rate ice volume loss of glaciers because it will ultimately affect downstream use of the meltwater and the livelihood on many people. The main research question for this study is "What is the ice volume loss on the debris covered, detached portion of the Reschreiter Glacier and what patterns are seen that can help us understand the future of this glacier?" Understanding the glacier dynamics of portions of the Reschreiter Glacier will play an important role in determining how to move forward in terms of water use.

There are several categories of previous work that are important for this research. The first is research showing that Andean glaciers and more specifically, Volcán Chimborazo, are changing in recent decades. Most glaciers experience seasons with separate accumulation and ablation time periods because of variations in temperatures, solar radiation and precipitation. Unlike most glaciers, glaciers on Volcán Chimborazo can experience ablation throughout the year because there is only a 2° C difference in temperatures between seasons and these average temperatures are high enough to cause melting

(Vuille et. al, 2008). With the rising temperatures due to climate change, the glaciers in the Andes are changing at an increased rate. Vuille et al. (2008) also explains how the future climate, with a potential rise in average temperatures of 4.5-5° C by the end of the 21st century, is going to affect the glaciers along with the use of water that comes from the glaciers. The overall ice area on Volcán Chimborazo is also changing in recent decades. A study conducted by La Frenierre and Mark (2017) shows that the total ice area on Volcán Chimborazo has decreased by 21% ±9% from 1986 to 2013. Clearly, the glaciers are experiencing change on Volcán Chimborazo, but in order to understand how they are going to have an impact, further, more accurate work, like the work we conducted in this research, needs to be done to determine how much and at what rate the glaciers are changing on Volcán Chimborazo, in the Tropics, and throughout the world.

A second category of previous work that is beneficial for this project comes from other research done using Unmanned Aerial Vehicles (UAV). Similar studies have been done using UAV technology on other glaciers. For example, studies have been conducted using UAV technology on the Forni Glacier in the Italian Alps by Fugazza et. al. (2015), in the Himalayas by Immerzeel et. al. (2014), on the Fountain Glacier in the artic by Whitehead et. al. (2013), and in Greenland by Ryan et. al. (2015). One main trend throughout these research projects was that using a UAV for data collection is a cost-effective alternative to satellite, LiDAR, or TLS and result in having high-resolution imagery that is similar to or better than the use of satellite imagery. While these UAVs are all different from the one used in this study, they are still found to be a very useful tool in the data collection process. These articles also address how accurate the DEMs created from the imagery can be compared to other methods that use LiDAR, Terrestrial Laser Scans or satellite imagery to create a DEM.

Research conducted by Ryan et. al. (2015) is helpful in terms of UAV information as well as using the same software to create the model of the glacier. The accuracy as well as difficulties of using the AgiSoft Photoscan Software are discussed in this article. Through this article it is clear that Agisoft Photoscan will create accurate DEMs that can be used for this type of study. In another article written by Li et. al. (2016), techniques that are used in the AgiSoft Photoscan Software are discussed. This article explains that using this software will create models of high accuracy in a short period of time. Additionally, this article goes through the process of creating the model itself. The book "Structure from Motion in the Geosciences" explains what the actual techniques that are used in the Agisoft Photoscan process. Agisoft Photoscan is a structure from motion photogrammetry software. The basic definition of this software is that it takes a pixel in one image, finds that same pixel in overlapping images, and then uses the angles to those other pixels to create a 3D surface (Carrvick, 2016).

The research conducted by Wigmore and Mark (2017) was crucial in the success of this research. The UAV used in our research was modeled off of the UAV used by Wigmore and Mark during their research in Peru studying the Llaca Glacier tongue and its proglacial lake system. We consulted with Oliver Wigmore to make adjustments to our UAV and camera script. We also talked to him throughout the image processing portion of the research that was done on Agisoft Photoscan.

Although glacier research has been conducted on Volcán Chimborazo in the past, there has not been a study that has used a UAV and studied the change in ice volume rather than the change in surface area of the glaciers. If the UAV is as good of a tool as previous studies suggest, the results of this research will be able to provide significant insight into how the Reschreiter Glacier has changed through time as well as how these changes will affect the use of meltwater from the glacier.

There are three overall goals of this research. The first is to determine the change of ice volume on the debris-covered, detached portion of the Reschreiter Glacier. The second is to discuss areas of significance across the surface of the glacier and what that means for the future of the glacier. Lastly, we hope to address the feasibility of using a UAV for this type of research in this type of environment.

Geologic Setting-

The Andes Mountain Range formed as a result of the Nazca Plate subducting under the South American Plate. This subduction started 140 million years ago. Roughly 45 million years ago mountain building occurred with the increase in volcanic activity. The Andes Mountain Range is 4,500 miles long and up to 500 miles wide and is also one of the tallest mountain ranges in the world (Kilian et al., 1995). It extends from northern to southern South American along the western coast.

The Andes consists of two mountain ranges, the Western and Eastern Cordillera. One of the mountains within the Western Cordillera of the Andes is Volcán Chimborazo, a stratovolcano. Volcán Chimborazo is located in central Ecuador (*Figure 1*) and has a summit 6263 meters above sea level. Because of the bulge of the Earth’s surface at the equator, the summit of Volcán Chimborazo is the farthest point from the center of the earth.

Figure 1- Volcán Chimborazo (seen in red) is located in Central Ecuador just north of Riobamba.

The elevation of Volcán Chimborazo allows glaciers to form on the mountain, despite its proximity to the equator. Volcán Chimborazo has 17 glaciers on it that extend downward from the 55-meter-thick ice capped summit in all directions (*Figure 1*). The Reschreiter Glacier (*Figure 2*), on the northeastern flank of the mountain, extends to the lowest elevation 4780m. 16% of the Reschreiter Glacier is debris-covered, and a total of 10% of it is detached from the main portion of the glacier. The total area of this glacier is 2.6km^2 (La Frenierre and Mark, 2017).

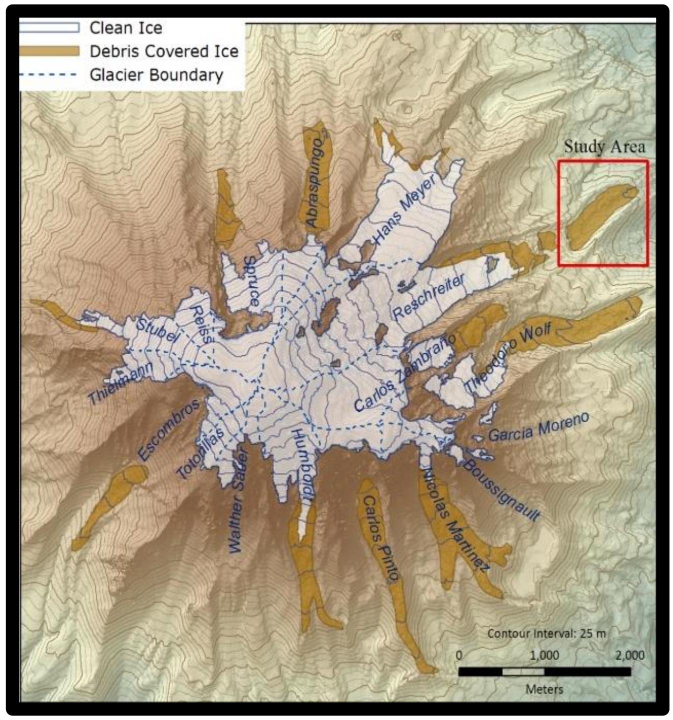

Figure 2- The Reschreiter Glacier extends to the northeast from the summit of Volcán Chimborazo, the study area can be seen on the right of the image in the red box.

Relatively high seasonal precipitation variability and low average temperature fluctuations create conditions under which small fluctuations in climate can produce dramatic changes in the glaciers. There is only a 2° C difference in temperatures between the warmest months of November and December and the coolest months of July and August. This, along with the fact that the temperatures are high enough to cause melting throughout the year, is responsible for the glaciers on Volcán Chimborazo experiencing ablation year-round. There are two wet seasons that extend from February to May and October to November. There is some precipitation during the intervening dry seasons, from June to September and December to January, but not enough to cause significant changes in accumulation of the glacier.

Being a mountain environment, the climate in this area varies at different elevations. There are four different zones that make up the climate of Volcán Chimborazo. Depending on the zone the glacier could receive more than 600mm of precipitation a year or much less than 600mm of precipitation a year and average temperatures can vary from subfreezing to 22°C (La Frenierre and Mark, 2017). The different climate zones are significant for the Reschreiter Glacier because of the lower elevation at its tongue. The tongue of the Reschreiter Glacier lies in the highest climate zone, but lies in close proximity to another climate zone just 200m in elevation downslope. With that being said, there can be variation in day to day temperatures, but still a minimal variation in the yearly average temperature and a significant variation in precipitation.

The Reschreiter Glacier is a part of the Upper Rio Mocha Watershed. The meltwater from the Reschreiter glacier eventually enters the downstream Rio Mocha River. This river then leads into a man-made, cement canal called Las Abras Canal, which transports the water to the communities downstream.

Figure 3- This UAV was designed specifically for high-elevation use. The flight controller can also be seen in the bottom right corner of this image.

Methods-

UAV description and specifications-

The UAV (*Figure 3*) used in this research was designed specifically for research at high elevations. Overall, this UAV was designed after a UAV built by Wigmore and Mark who conducted similar research in Peru (Wigmore and Mark, 2017). The reason a UAV was built rather than purchased is because there are few UAVs, if any at all, that are designed specifically for high elevation flights. This UAV was constructed with a carbon fiber frame, arms, legs, and rotors to decrease overall weight and increase flight time. Without the battery the UAV weighted 2.5kg. The UAV was powered by a 10000 MAH 4S lithium polymer battery that allowed for roughly 8-9 minute flight times at about 4000-5000m.a.s.l. The flight controller in the UAV was a 3DR PixHawk, which allowed for autonomous flight of the UAV. To navigate the UAV when it was not flying autonomously, a 2.4GHz FrSky Taranis Plus radio controller was used. The Mission Planner software, which was downloaded onto our field computer, was also used to maintain communication between the UAV and radio controller. Mission Planner was used to create flight paths for the UAV. With our specific camera settings and an average flight speed of about 8m/s, flight paths were created so that images that were taken next to each other overlapped 75% and side lapped 60%. This was done to ensure full coverage of the glacier and if need be, blurry images could be removed from the analysis. A total of eight flights were conducted to get full coverage of the glacier surface (*Figure 4*).

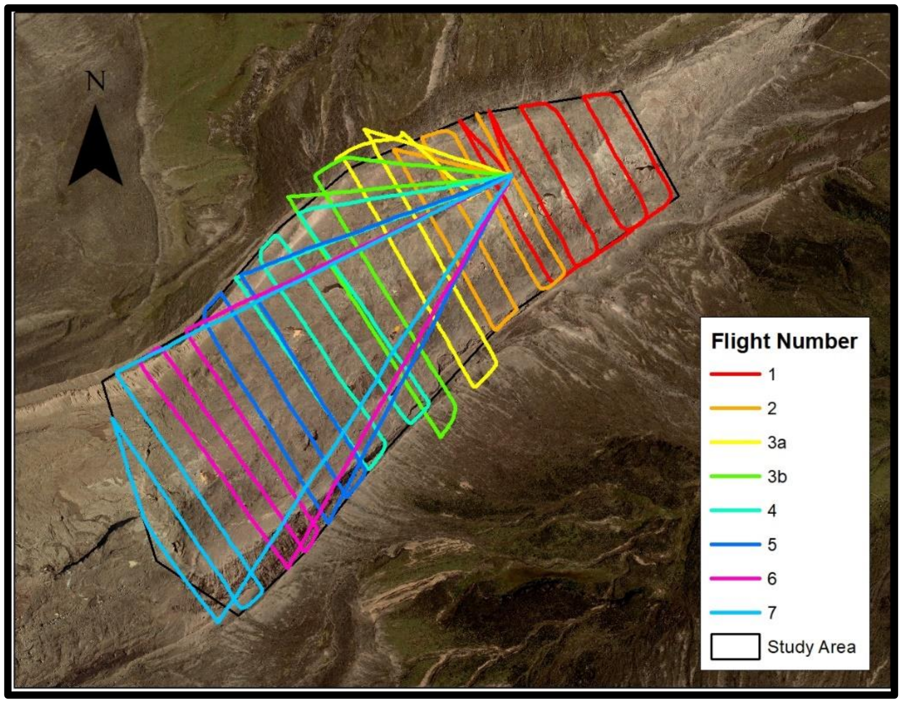

Figure 4- Each of the eight flight paths can be seen here. As you can see from the flight paths, the UAV took off and landed in the same location each flight.

For data collection, the UAV was equipped with a Canon S110 Powershot camera. This camera allows for use of the Canon Hack Development Kit (CHDK), which is a firmware that is loaded onto the

SD card that uses a script to manually set the specifications of the camera. The CHDK was used in order to minimize blurry images as well as set an interval for when the camera should take pictures. The specific script that was used was the kap_uav.lua. The settings that were manually set were the ISO at 200-400, the F-stop at >4, an image capture every 3 seconds, and the shutter speed at >1/1000s. These settings were used based on the work of Wigmore and Mark (2017).

Ground Control Points-

Prior to the 8 UAV flights, ground control points (*Figure 4*) were placed across the surface of the glacier. A total of 14 ground control points were spaced out across the surface of the glacier as well as on the moraines. The ground control points were secured in the ground using 6-inch nails and were placed on surfaces that were relatively flat. These ground control points were later used to georeference the DEM that was created using Agisoft Photoscan. The exact location of each of these ground control points was determined using a Topcon Hiper SR base station, located on the north moraine of the glacier, and two Topcon Hiper SR rovers with Topcon FC 500 field controllers. Each ground control point had a total of 300 DGPS readings to maximize location accuracy.

Digital Elevation Model Creation-

In order to create a DEM for the ice volume change analysis, the images collected from the UAV were imported into the Agisoft Photoscan software. This software uses structure from motion algorithms to create orthomosaics and DEMs. The exact workflow that was followed is from Agisoft LLC, but is also described in previous studies (Wigmore and Mark 2017; Ryan et. al., 2015; Li et. al., 2016; Immerzeel et. al., 2014). The general workflow that we used was as follows-

1. Import images into Agisoft Photoscan. A total of 1,177 images of the Reschreiter Glacier were imported for use.
2. We aligned images using an accuracy setting of "high," key point limit of 120,000, and a tie point limit of 25,000.
3. The ground control points were imported and found on the aligned surface of the images. Step 2 was then repeated using the images as well as the ground control points to georeference the alignment of the images.
4. A dense point cloud was then created using the quality setting of "high" and a depth filtering mode of "aggressive."

5. The DEM was then created using the dense point cloud. The settings of this were interpolation set at “enabled” which calculates an elevation at all points of the DEM. The DEM that was created had a resolution of 0.06cm.
6. The DEM was then exported to be used in ArcGIS for DEM comparison.

The 2012 DEM that was used in this analysis was collected by La Frenierre (2017). This DEM was created using a Terrestrial Laser Scanner (TLS). This DEM (*Figure 5*) does not get full coverage of the glacier because some areas of the glacier are behind small hills of debris covered glacier and TLS only collects data that is visible to the laser scanner. This DEM has a resolution of 0.5m.

Ice Volume Change Analysis-

ArcGIS was used to conduct the DEM comparison to determine the ice volume change of the Reschreiter Glacier. First, both the 2012 and 2017 DEMs (*Figure 5*) were clipped to the study area boundary to make sure only the surface of the glacier was being studied. Next, the 2017 DEM was resampled to have a 0.5m resolution to match the 2012 DEM as well as being snapped to the 2012 DEM so all pixels on both DEMs would be aligned for comparison. The 2017 DEM was then subtracted from the 2012 DEM using the Raster Calculator tool to create a change in elevation surface (*Figure 7*). Negative numbers on this surface represent loss of elevation while positive numbers represent gain in

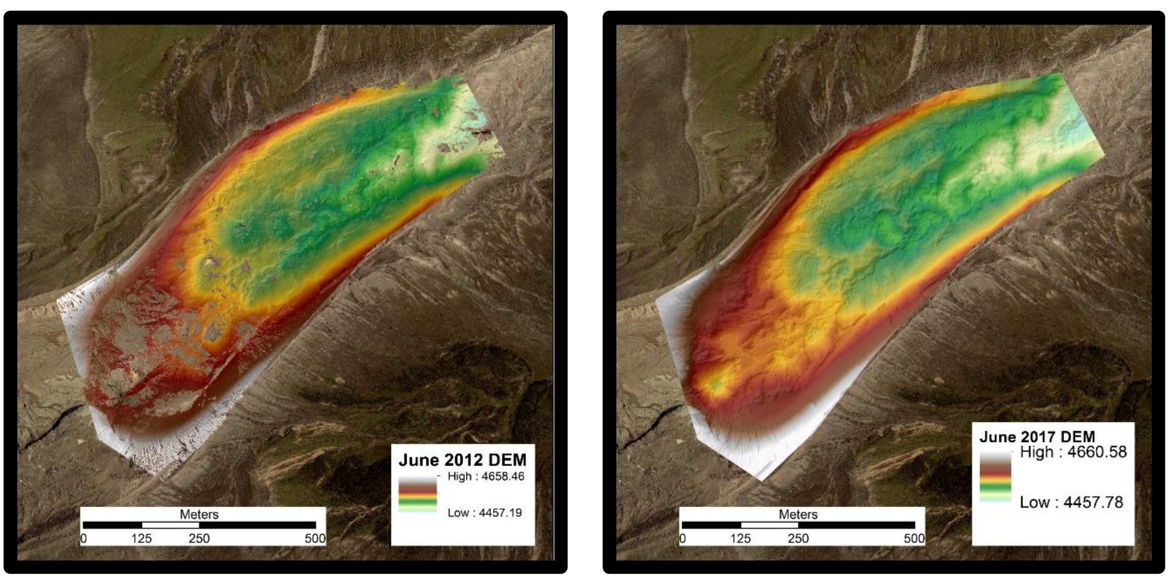

Figure 5- The DEM from 2012, which was created using the TLS can be seen on the left. There is not full coverage of the study area as compared to the DEM created from the images collected from the UAV, as seen on the right.

elevation. The total volume change was then calculated by taking the area of a single pixel multiplied by the total elevation loss of the glacier surface.

Results-

During the Agisoft process, 6 of the 12 ground control points were located and used for aligning and georeferencing the DEM. The elevation error for the georeferencing portion of the Agisoft process from these 6 points was 0.59m. The 2017 DEM created using the Agisoft process has a maximum elevation of 4660m and a minimum elevation of 4457m. The 2012 DEM obtained using the TLS has a maximum elevation of 4658m and a minimum elevation of 4457m. There is a difference in maximum and minimum elevations in these DEMs because, again, the 2012 DEM does not get full coverage of the glacier surface. Before resampling the DEM from 2017 to 0.5m resolution, it had a resolution of 0.07m.

We used techniques by Pieczonka et.al. (2012) to conduct an uncertainty assessment of the change in elevation DEM. To do this, we determined there should be no change in elevation on surfaces showing bedrock as well as stable moraine surfaces that have a slope of less than 10% that occur in both the 2012 and 2017 DEMs. The points determined to be no change were then used for the uncertainty assessment. The points that should have shown no change had values of change in elevation from less than 0.25m to greater than 2.0m. Though points beyond two standard deviations of the mean are often removed from error analysis estimates (Pieczonka et al. 2012), a clear spatial pattern was evident in the distribution of these no change points on the surface of the glacier (*Figure 6*), thus values beyond two standard deviations of the mean were not excluded from our error estimate. We still used two standard

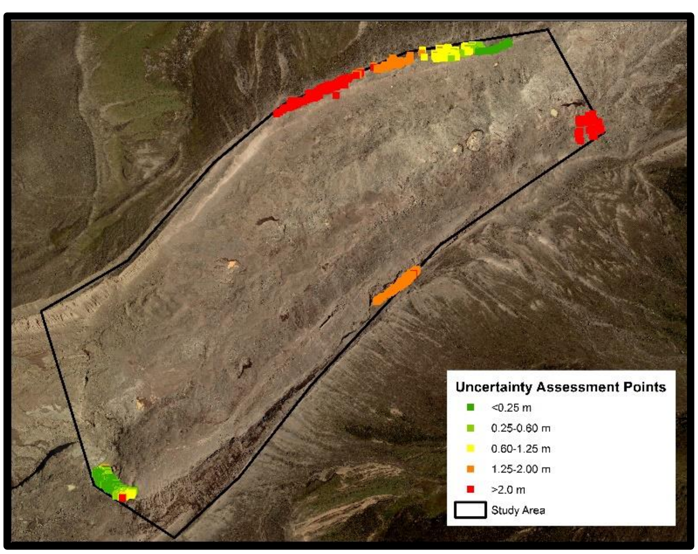

Figure 6- Map of points used for uncertainty analysis. Colored regions show areas of exposed bedrock or areas with stable slopes in both the 2012 and 2017 DEMs that are expected to have experienced no change in elevation. Warmer colors show greater observed differences; cooler colors show smaller differences

deviations from the mean or the 68.3 percentile of the data points to find an uncertainty in the elevation change DEM of ±0.55m.

The change in elevation DEM (*Figure 7*) shows both areas of ice volume gain and loss. Much of the gain in elevation is seen near the tongue of the glacier and along the southern lateral moraine of the glacier. Areas of elevation loss are seen across the glacier surface. Two areas of significant loss are seen on the northern lateral moraine and near the exposed rock face on the western surface of the glacier. Based on the change in elevation DEM, a total ice volume loss of 790,000m^3 ±172,000m^3 occurred between June 2012 and June 2017. This is an average elevation loss of 2.55 ±0.55m per 0.25m^2 of glacier surface and a maximum elevation loss of 22.95 ±0.55m in a 0.25m^2 glacier surface area. Because the 2012 DEM has missing data points, these parts of the glacier could not be assessed, and are therefore absent from final elevation change DEM.

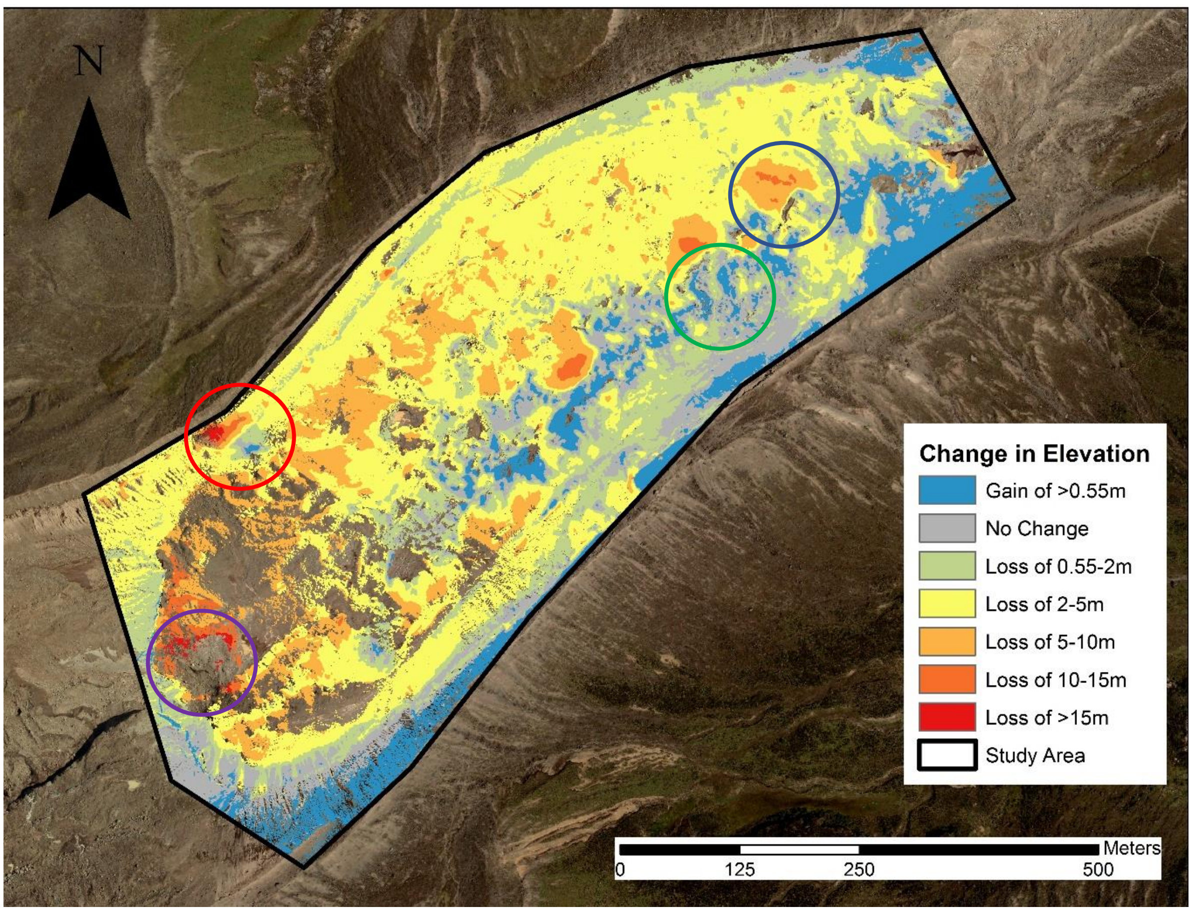

Figure 7- DEM showing the change in elevation across the Reschreiter Glacier. Warmer colors represent greater loss of elevation; cooler colors represent elevation gain. There are clear spatial patterns across the glacier surface. Areas of significance are identified by the colored circles; see Discussion for details.

Discussion-

Based on the Change in Elevation DEM from the results (*Figure 7*), there are areas of significance on the surface of the Reschreiter Glacier. These changes have played a key role in how the glacier has changed in the past and will continue to do so into the future. The goals of this research, which are to determine the volume loss of the Reschreiter Glacier from 2012 to 2017, discuss the areas of significance on the surface of the glacier and to report the feasibility of using a UAV in this type of field research, will be addressed here in relation to our overall research question which was "What is the change in ice volume on the debris covered, detached portion of the Reschreiter Glacier, and what patterns are seen that can help us understand the future of this glacier?"

Areas of Significance on the Glacier Surface-

There are four main areas of significance that are seen across the surface of the Reschreiter Glacier, two of which: ice cliffs and proximity of ice to exposed bed rock, can account for major changes in elevation and continual ice melt into the future. The other two areas of significance are the over steepening of the moraines and various debris thicknesses on the surface of the ice.

The first area of significance is circled red in *Figure 7.* This represents a substantial rock slide or debris fall. In this case the lateral moraine of the glacier is no longer buttressed by ice and is over steepening due to increased rates of erosion on the moraine. Similar to rock slides, the movement of large boulders can also be seen on the surface of the Change in Elevation DEM. Since this was over a five-year time frame, movement like this was seen a number of times across the surface.

Another area of significance is displayed by the purple circle in *Figure 7*. This area represents the bedrock that was exposed after the debris covered section of the Reschreiter Glacier detached from the main glacier upslope to the southwest. This exposed rock has a lower albedo. Because of its lower albedo, the bedrock stays warmer longer which results in the surrounding ice melting more around this area as compared to areas not near the bedrock. This area represents the section of the glacier with the highest change in elevation as well as an area on the glacier with significant ice volume loss. As the ice near this rock face continues to melt, more of the rock face is exposed creating a positive feedback of melting. This area of the glacier could also be affected by the runoff from the glacier upslope. The moving water runs off the rock face, through the debris, and onto and through the glacier creating more melt as there is more runoff from above.

The third area of significance on the glacier surface is the ice cliffs. When there is any exposed ice on small hills or cliffs on the glacier surface the ice begins to melt. As this ice melts, the debris that was on top of it falls down the cliff. This exposes more ice, this ice also melts which makes more debris fall. This same process was seen and described by Immerzeel et. al. (2014). Immerzeel et. al. (2014) also describes that these features account for large amounts of ice volume loss for features that cover only small areas of the glacier surface. This process also creates a positive feedback of melting of the glacier. This process is very evident on the surface of the glacier and can be seen in the blue circle (*Figure 7*) by the tongue of the glacier.

The final area of significance is circled in green in *Figure 7*. This is an area where there is some gain, some loss, and some areas of no change. One explanation for this is that in this area there could potentially be minimal to no ice left and we are just seeing rock movement, or this area is controlled by the debris covered nature of the surface and there is minimal change here because of the thickness of the debris cover.

Glacier Change Comparison-

While features found on glacier surfaces are similar throughout the world, as described above, all glaciers are different in terms of location, elevation, size, etc. Other studies can be looked at to see how glaciers on Volcán Chimborazo relate to them in terms of ice volume change and overall behavior. The study conducted by Whitehead et. al. (2013) on the terminus of the Fountain Glacier on Bylot Island in the Artic took place over one year from 2010 to 2011. Being a year-long study, the elevation changes seen are not as significant as those seen on the Reschreiter Glacier. From 2010 to 2011 the elevation changes were mainly between 1.5m to 2.5m in elevation loss. Wigmore and Mark (2017), whose work is in the Andes over a one-year time frame on a debris covered glacier as well, found a mean elevation loss of 0.75m, a maximum loss of 18m and a maximum gain of 11.5m as well as a total ice volume loss of 156,000m^3. Although you cannot directly compare this to the Reschreiter Glacier because of differences in size, location, and number of different surface features on the glacier, if you take the volume of ice loss from Wigmore and Mark (2017) and multiply it over 5 years you get a similar ice volume loss to the Reschreiter Glacier. Even though glacier change can be highly variable over months to years, this suggest that glaciers in the area are responding similarly to the Reschreiter Glacier on Volcán Chimborazo. Glaciers in similar regions of the Andes are experiencing melting and the more glaciers in the Andes that can have research like this conducted on them can result in a better overall understanding of glacial ice volume loss in the tropics to better influence local and regional use of the runoff from the glaciers in an area greatly impacted by climate change.

Role of Debris Cover on Ice Volume Loss-

The debris covered nature of the Reschreiter Glacier has an impact on the rate of ice volume loss. The thickness of debris cover on the Reschreiter Glacier was not collected, but during the research there were areas of exposed ice with millimeter to centimeter layers of debris on top of it as well as large piles of sediment from fine grains and pebbles to large boulders. Overall, the debris cover on the glacier is not uniform across the surface because of the different surface features we see on the surface such as areas of exposed ice, ice cliffs, and areas of more or less melting. The moraines are most likely eroding at different rates which affects the thickness of the debris cover on the surface. According to Takeuchi et. al. (2000) debris thicknesses of 10cm slowed the melting of the Khumbu Glacier by 40% as compared to bare ice on the same glacier. Other studies conclude that with increased debris thickness there is a decrease in ablation due in part from the insulation effect of the debris cover on the ice (Benn et. al., 2012, Shahi et. al., 2015, Wigmore and Mark, 2017, Juen et. al., 2014, and Pratap, et. al., 2015). Based on this it is clear there are varying thicknesses of debris cover that are affecting the rate of ice melt on the Reschreiter Glacier. Even though this debris layer does not stop completely stop the ice melt, it could potentially increase the longevity of ice on this glacier. As you move towards the tongue of a glacier debris cover is usually thicker (Benn et. al., 2012). Less melting near the tongue of the glacier could be accounted to this. Another factor that could help the insulation of ice near the tongue is the over steepening in the moraines. More debris that erodes from the moraines of the glacier can increase the thickness of debris on the glacier and increase the insulation and decrease ablation as compared to clean ice. Future studies could take measurements of debris thickness to further address debris cover on the Reschreiter Glacier.

UAV Feasibility-

The use of the UAV was very beneficial for this research. The UAV, like other studies have concluded, is a useful tool to be used for data collection in a broad spectrum of fields (James and Robson, 2014, Koh and Wich, 2012, Remondino et. al., 2011, Watts et. al., 2012, Eisenbeiss and Sauerbier, 2011, Wigmore and Mark, 2017, Fugazza et. al., 2015). Like previously mentioned, other methods of data collection, such as LiDAR, or satellite imagery, could have provided similar results, but at a different expense, most likely in a longer time frame, and not with the same ease as using a UAV.

While all methods of data collection in this type of research need fairly clear skies and no fog above the ground, the 8-minute flight times of the UAV allow for flights in shorts breaks in weather.

Although the UAV was a great tool to use for data collection, there are some things that we, as a research team, need to address before taking it back to the field. Battery life and flight times are very important for this research. Only 8 batteries could be brought to Ecuador which means 8 flights and

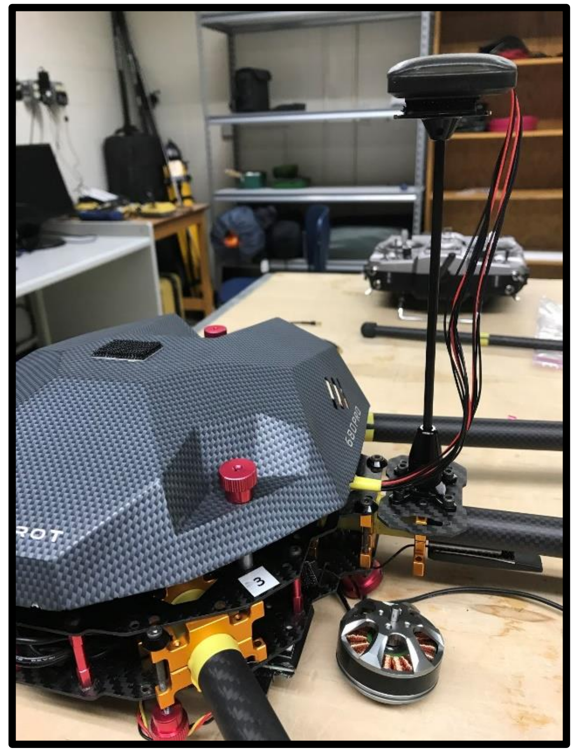

Figure 8- During the field research the GPS was located on the cover of the UAV, which can be seen in the image on the left. The new location of the GPS, image on the right, makes the inter-components of the UAV more accessible.

roughly 64 minutes of flight time. While this was enough for the research this year, future trips could have issues with battery life and the number of flights needed with the UAV. To address this for future trips to Ecuador, a generator will be brought into the field to allow for the charging of the UAV batteries to ensure the entire glacier surface can be flown over with the UAV. The UAV did not crash or need any repairs during this research either. We were very fortunate that this was the case, but know the UAV will need repairs in the field at some point. Because of this, instead of bringing only spare UAV parts into the field, a second, complete UAV will also be brought with the spare parts in future work.

There are two modifications that will be made to the UAV for future work. This first of which is to change the location of the UAVs GPS, is already complete. During the research the GPS was located on the cover of the UAV (*Figure 8*). This made it difficult to access the parts under the cover of the UAV. The new location of the GPS is on a mast located on the arm of the UAV (*Figure 8*). This mast easily lays flat for transport and no longer creates difficulties when accessing the parts under the cover of the UAV. The second modification to the UAV will be the camera gimbal. Currently the camera is connected straight to the UAV, so movement in the UAV from wind results in movement of the camera. When the camera moves, it no longer points straight down, but rather at an angle. A new gimbal will ensure the camera is always pointing straight down no matter the movement of the UAV. A landing pad of some sort will also be brought and used on future research to ensure a flat and more level takeoff and landing surface for the UAV (See **Appendix A** for further UAV training information and examples).

Ground Control Points and Agisoft Photoscan-

The Ground Control Points (GCPs) did cause some issues for the Agisoft Photoscan process. As mentioned in the results section, only 6 of the total 14 ground control points were located in the Agisoft Photoscan process (*Figure 9*). There are two problems that arose with only locating 6 of the GCPs. The first problem is that there is not as much spatial distribution across the glacier surface with only 6 points. More spatial distribution would have helped create a more accurate DEM surface which in turns helps create a more accurate Change in Elevation Surface and Ice Volume Change. The second issue is that there were not enough GCPs collected to allow for there to be check points. Check points would not have been used in the alignment process of Agisoft Photoscan, but would rather be used after the creation of the DEM to check points on the DEM for accuracy. Based on the location and elevation of the check points in comparison to the same point on the DEM, the accuracy of the DEM could be found. So, there was only an uncertainty assessment done on the Change in Elevation DEM and no accuracy assessment for the 2017 DEM created using Agisoft Photoscan. The physical GCPs that were placed on the surface of the glacier are what caused issues in the Agisoft Photoscan process. The reddish-pink plates with yellow X's on them (*Figure 10*) were difficult to locate against the reddish, brown and tan color of debris on the surface of the glacier. To fix this, for future work we created new GCPs (*Figure 10*) that are larger which will create greater visibility for them to be found in the Agisoft Photoscan process. Another aspect that will help to locate the GCPs is to make sure the UAV is always facing the same direction during the flight, this can be done in the Mission Planner

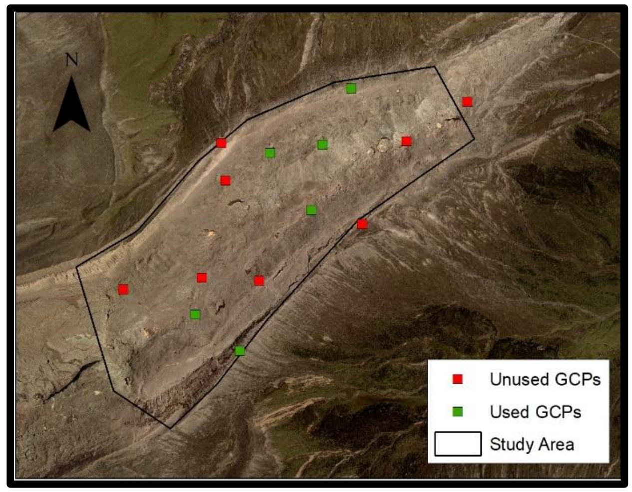

Figure 9- All of the GCPs can be seen on the glacier surface here. Green squares represent the GCPs that were found and used in the Agisoft Photoscan Process. The

software in the flight plan. With the UAV always facing the same direction, the orientation of all the images will be the same. This will help in locating the GCPs in Agisoft Photoscan as well.

Figure 10- The new GCPs, seen in the left image being compared to the old GCPs, that will be used will be much more visible on the surface of the glacier as compared to the old GCPs seen in the image on the right.

Conclusion-

The Reschreiter Glacier was once a reliable reservoir of water for neighboring communities, now this reservoir has decreased in volume and will continue to do so for the foreseeable future. The surrounding communities will need to acknowledge and adapt to these changes in meltwater from the Reschreiter Glacier as well as other glaciers on Volcán Chimborazo and throughout the Tropical Andes. Further studies addressing the interaction of glacial meltwater, groundwater, and springs will help to determine how significant the ice volume loss on the Reschreiter Glacier truly is to the many people that rely so heavily on it for their daily needs. The UAV proved to be a viable tool for data collection at high elevation, remote locations. Slight changes will be made to the UAV to increase its effectiveness while being used in the field in future research. The UAV, paired with Agisoft Photoscan, created a high-resolution DEM surface that was used to determine the ice volume change of the Reschreiter Glacier. This process can be used in the future to continue to address the changes to ice volume on the Reschreiter Glacier.

Appendix A-

Example of Further Training Prior to Field Work

One important thing to understand is that this was the first time using this UAV for research and I, as the pilot of the UAV, had no prior experience flying UAVs until a month before taking the UAV to Ecuador. With the being said, more training needs to be done prior to the field research to ensure everyone is comfortable with the UAV and other programs used in the field. Currently, a repair and training manual for the UAV is being created to ensure better knowledge of the UAV for everyone involved. One example of how more training or more time before the research would have been beneficial can be seen in the example that follows; after turning the UAV to the autonomous flight mode during the first flight in Ecuador, the UAV started flying back toward Minnesota because one step was missed in the pre-flight process. This small error could have been detrimental because we only have a certain number of batteries and each one could only be used for one flight. The battery from this flight was later used for a shorter flight.

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