Cryoconite Evolution and Formation on an Arctic Glacier Surface: A Case Study and Model

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0.1 Acknowledgments

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Chapter 1

Introduction

Cryoconite holes are vertical cylindrical holes that form on glacier surfaces due to the lower albedo of sediments. Cryoconite holes exist on Linnébreen, Svalbard over the entirety of the glacier. They preferentially melt below the surrounding glacier surface and eventually create standing water above them. In this study, six cryoconite holes were created by placing sediments on the glacier surface and observing their growth and movement for a period of fourteen days. They ranged from 2.0 cm wide with a depth of 0.5 cm to 7.0 cm wide and a depth of 2.0 cm. The greater the size of the cryoconite, the more it enhanced the melting of the surrounding surface both where it was initially placed and when it traveled down glacier. The largest cryoconite hole finished the two-week period 1 m down glacier from its initial placement and melted nearly 10 times the area of glacier ice as its own initial area. I hypothesize that this is due to the hydrologic cycle at work on the glacier. In order to look at this, we modeled how the cryoconite holes would form using the lower albedo of the cryoconite and the sun's revolution about the field site.

1.0.1 Research Project: Svalbard REU

This research began and is part of the Svalbard Research Experience for Undergraduates (REU) program run by Steve Roof, Al Werner, Mike Retelle and Julie Brigham-Grette. The program receives funding from the National Science Foundation with a 10-year grant to encourage and fund undergraduate research opportunities starting in 2004. Svalbard REU also works in close collaboration with the University Center on Svalbard (UNIS), the home base in Longyearbyen, Svalbard.

All students work on individual research projects that they develop themselves with the help of the faculty advisors and fellow student researchers. The objective of the program is to understand how a high latitude glacier system (the glacier, melt-water streams, and glacial lake) responds to climate change. Each summer the program brings six new undergraduate

Figure 1.1: *Linnébreen. Photo taken on August 10^{th}, 2010, facing South.*

students to the site and each of them conducts his or her individual research project.

1.0.2 Previous Cryoconite Research

Cryoconite holes are vertical, cylindrical holes that form on a glacier surface when windblown or trapped sediments collect on the surface and preferentially melt into the glacier surface. The word originated from a Swedish explorer, A.E. Nordenskjöld, who named them using Greek: 'cryo' meaning ice and 'konos' meaning dust (MacDonell and Fitzsimons, 2008). On Linnébreen, cryoconite holes are visible most noticeably in the ablation zone during the summer months; however, when the snow melts off the top of the glacier near the end of the summer, cryoconite holes are visible there as well. While in Antarctica cryoconite holes are ice-lidded and thus isolated from the air above them, all cryoconite holes on Linnébreen, Svalbard (during the summer months) are open to the air. While most of them have standing water above them quite a few did not; instead, any water present was well mixed with the sediments.

In Antarctica, Fountain found that cryoconite holes formed 4-6% of the surface in ablation zones on the four glaciers he studied in Taylor Valley, Antarctica (Fountain et al., 2004). The cryoconite holes he studied varied in diameter from 5 to 145 cm and in depth from 4 to 56 cm. Some, however, formed huge holes with a diameter of 30 m and depth of 5 m; these huge holes would have ice lids as thick as 36 cm. Nearly one-half of the holes were connected to the near-surface hydrologic system while the rest were isolated throughout the year. In Taylor Valley, the near-surface hydrologic system lies tens of centimeters below the actual ice surface, and the glacier surface is generally frozen and dry, unlike the glaciers seen in Svalbard (Fountain et al., 2004).

In order to estimate how much the cryoconite holes contributed to the glacier runoff,

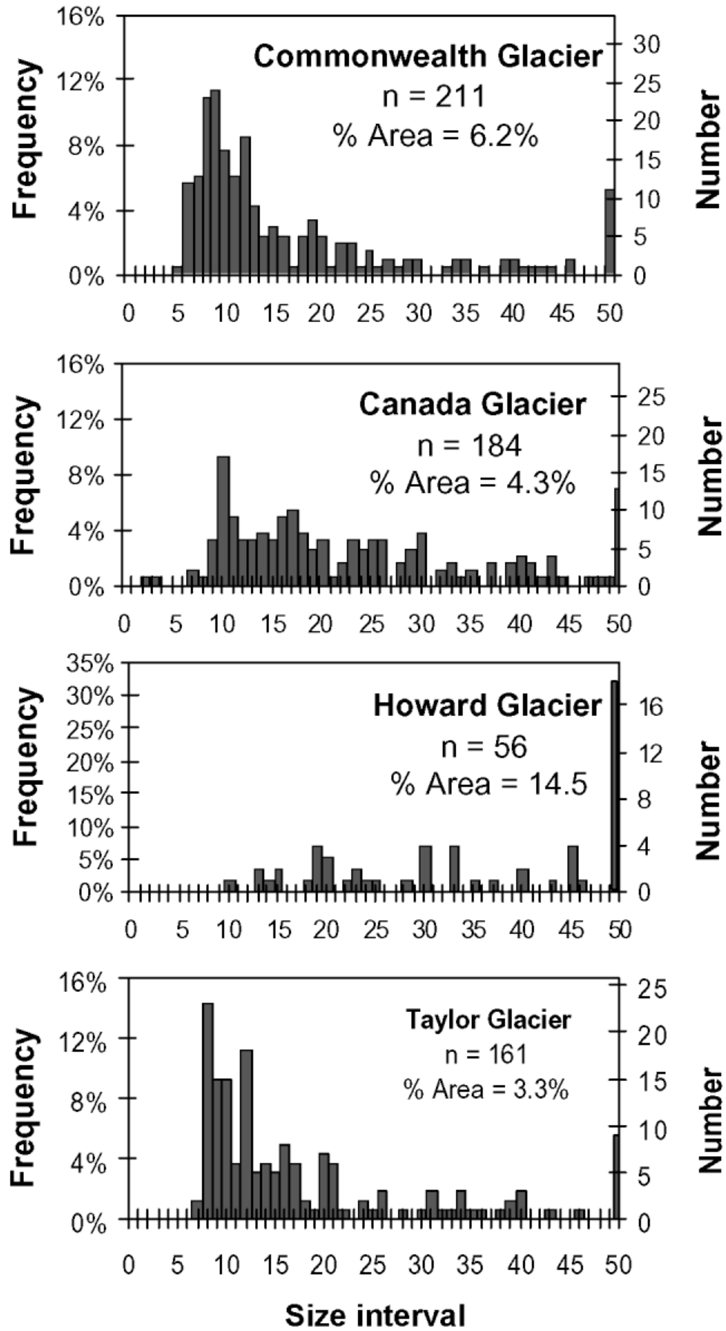

Figure 1.2: *Frequency distribution of cryoconite hole diameters on the four glaciers in Fountain's study in Taylor Valley, Antarctica. (Fountain et al., 2004)*

Fountain attached a 5 m long rope to several ablation stakes in the ablation zone and all the cryoconite holes within the 5 m radius circle were measured. They only recorded the diameter of the holes, not the depth or the thickness of the ice lid. However, all of the holes they measured were covered by an ice lid and were circular in shape. Fountain did this for four different glaciers (Commonwealth Glacier, Canada Glacier, Howard Glacier and Taylor Glacier) and he found that the diameters of the holes were statistically different for the different glaciers (Fountain et al., 2004). The Taylor and Commonwealth Glaciers had holes of smaller diameter, while Canada and Howard Glaciers had a flatter distribution of diameters (see Figure 1.2).

Fountain hypothesized that the difference in diameters among the different glaciers was due to a difference in sediment fluxes and sources. He suggested that the smaller cryoconite holes were probably formed by aeolian sediment sources (because they are easily distributed) while the larger holes might be due to avalanching. On Linnébreen, while avalanching did occur and brought sediments to the glacier surface, this generally occurred only on the sides of the glacier. Since the sides of the glacier were so thin, the sediment transported there by avalanching would generally melt through the entire glacier and either form a small glacier stream or simply settle on the ground. Very rarely would they form cryoconite holes. Many of the avalanches transported large rocks to the sides of the glacier, which instead of melting the surface would instead insulate it, slowing down the melting process (Fountain et al., 2004).

Fountain also looked at the changing depth of the cryoconite holes in Taylor Valley (see Figure 1.3). Fountain chose three cryoconite holes in the middle of the ablation zone on Canada Glacier and measured them periodically for about a month. He was able to use the ice surface as a proxy measure of the water surface because the ice covers were very thin and would reform if the water level changed substantially (Fountain et al., 2004). In general, the cryoconite holes in Taylor Valley showed only minimal evolution in depth over the course of the month of January (Antarctic summer), unlike the cryoconite holes seen on Linnébreen. This suggests that the cryoconite holes on Canada Glacier had reached an equilibrium state where they were far enough into the glacier that they no longer received enough sunlight to melt farther into the glacier faster than the glacier surface itself was melting.

Due to his findings, Fountain hypothesized that cryoconite holes undergo an annual cycle. The holes reach a maximum depth in late summer when air temperatures are at their highest and the amount of sunshine is at its maximum. In the early fall, temperatures drop and ice or snow covers the holes and the water in the holes freezes. During the winter months, sublimation occurs, ablating the glacier surface so that by late spring the sediment is at its shallowest depth. When the air temperatures begin to warm in the spring, the ice temperatures also increase and warm to the melting point. Then the sediment melts into the ice more rapidly than the ice surface, and thus the holes deepen and begin the cycle again (Fountain et al., 2004). This cycle is something I will study in the model created for my research.

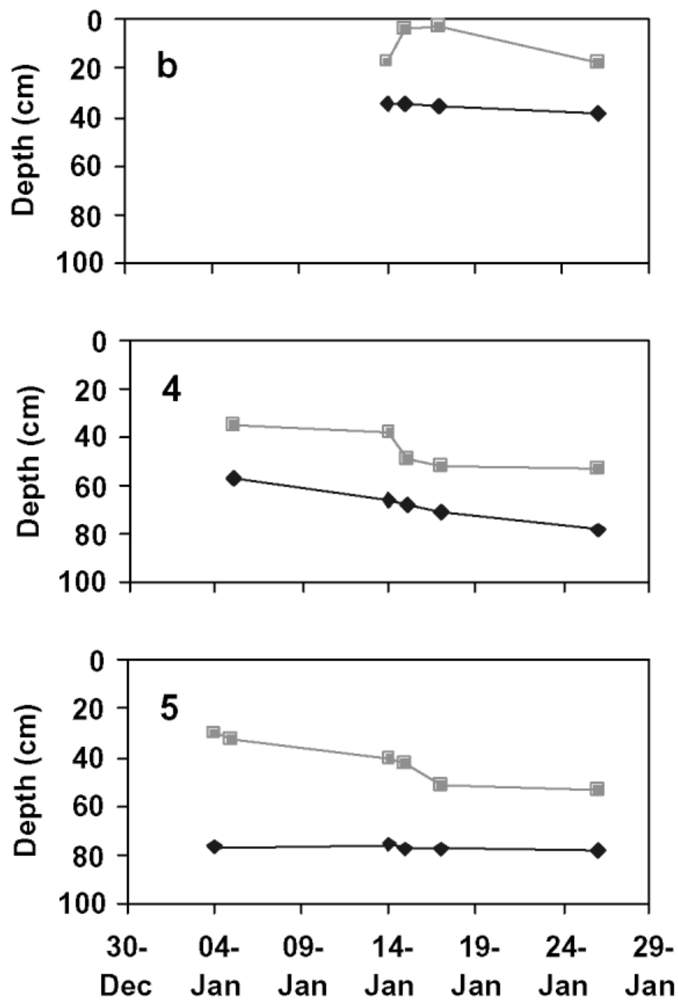

Figure 1.3: *The three graphs above measure the distance to the ice surface of the cryoconite hole, a proxy for the water surface(squares), and to the sediment layer at the bottom of the hole (diamonds). The diameter of the first cryoconite, b, is 25 cm; the diameter of cryoconite 4 is 150 cm and the diameter of cryoconite 5 is 60 cm. (Fountain et al., 2004)*

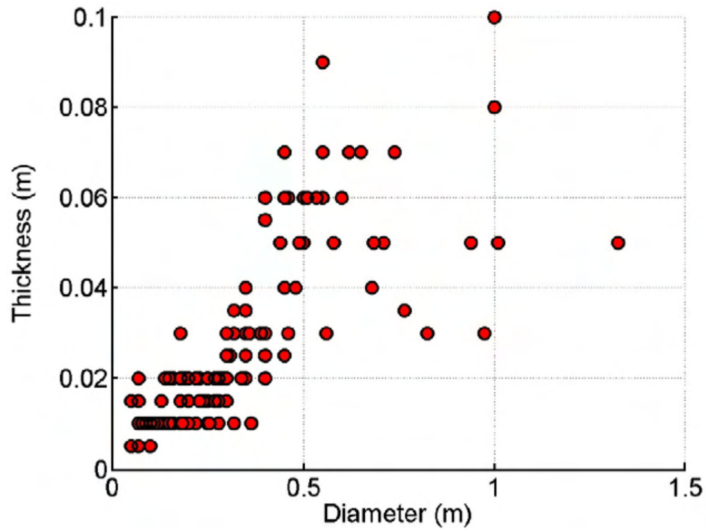

Figure 1.4: *Measured relation between the cryoconite thickness and diameter. (Brandt et. al. 2009)*

Other studies have looked more specifically at how the amount of sediment affects the size and depth of the holes formed. Brandt et al. measured many cryoconite holes using Ground Penetrating Radar (GPR) at the Jutulsessen blue ice area in Dronning Maud Land, Antarctica (Brandt et al., 2009). She found that the thicker the sediment, the greater the diameter of the hole (see Figure 1.4).

A study done by Conway & Rasmussen in 2000 more specifically calculated how much ice supraglacial debris could melt per day on Khumbu Glacier, Nepal. They found that surface debris temperatures could be up to 35°C higher than the air temperature; the energy transfer into the debris was mostly through the solar radiative flux and heat flow beneath 0.2 m was mostly through conduction. By measuring the thermal diffusivity and the volumetric heat capacity, they were able to estimate the thermal conductivity of the debris (k). They got two different values at two different sites. The first site had debris 0.40 m thick with an average temperature gradient of $\delta\bar{T}/\delta z = 19K/m$ and the the thermal conductivity was estimated to be 0.85 ± 0.20 W/Km which was sufficient to melt 4-6 mm of ice per day. The other side had debris with thickness of 2.5 m and a temperature gradient of 4.5 K/m, giving a thermal conductivity of 1.28 ± 0.15 W/Km which could melt less than 2 mm of ice per day (Conway and Rasmussen, 2000). These values are much smaller than what I measured on Linnébreen where the sediments could melt several centimeters in a day. The thickest of my cryoconite, however, was only 0.02 m which suggests that the thicker the cryoconite the more insulation occurs.

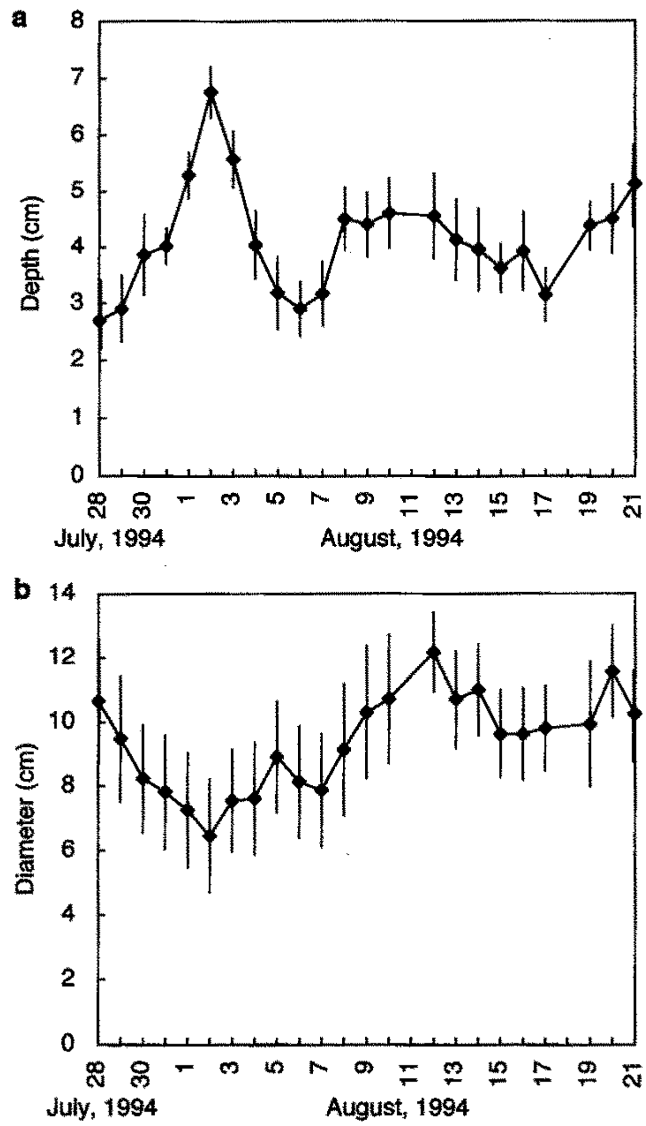

Figure 1.5: *Daily depth and diameter change of cryoconite holes at 5240 m on Yala Glacier, Nepal (Takeuchi et. al. 2000).*

Other cryoconite research has been conducted on Yala Glacier in Nepal. Takeuchi et. al. monitored seventeen holes over a period of twenty-five days and found that they were often short-lived and unstable. Over the observation period, 13 holes were broken. They also found that hole depth increased when snow fell since the snow increased the surrounding ice surface's albedo, further emphasizing the difference between the albedo of the ice and the cryoconite. Hole depth was not affected by the heat balance of the glacier surface and there was a negative correlation between hole-diameter and surface inclination, suggesting that the life span of the holes on steep slopes was shorter than those on gentle slopes. Overall, they hypothesized that the cryoconite holes were shallow and unstable because the changing albedo of the surrounding glacier surface. Unlike in Antarctica summers, in Nepal, the albedo of the surface was constantly changing because of the amount of dark-colored material, snow fall, and the relocation of material; all three phenomena occur on Linnébreen, Svalbard as well. The depth values measured over the 25 days of observation also varied a good deal and are very similar to the values found during my two-week observation period (Takeuchi et al., 2001).

Despite the recent increased attention toward cryoconite, little is known about their formation and evolution. And even less is known about cryoconite that is not permanently covered by ice. The condition of constant surface melt, rain and sediment transportation on Linnébreen, Svalbard creates unique conditions for the study of cryoconite. Rather than the cylindrical shapes you see on drier glaciers (Fountain et al., 2008), cryoconite holes were all of varying shapes and they never became larger than 15.0 cm across. The purpose of this study is to see how different amounts of sediment can affect the evolution of these cryoconite holes and how this might be modeled given the evolving topography and the sun's low revolution at 78° North.

1.0.3 Field Site: Linnébreen

Linné Valley is located 5 km from Kapp Linné on the eastern side of Spisbergen, Svalbard at the outermost part of the Isfjord. The glacier, Linnébreen is located at 77.9°N and 13.9°E. Average summer temperatures range from 0°C to 15°C. The hottest month of the year is July when the average temperature is 7°C. The coldest temperatures occur in March, where the average monthly temperature is -15°C. The wettest month occurs in August when an average of 40 mm of rainfall falls in the span of 10 days.

Currently, the temperatures in the Arctic are increasing more than anywhere else observed on Earth; and future projections suggest that this warming trend will continue into the 21st Century. Svalbard, with 60% of its land covered in glaciers (~36,000 km^2), is one of the largest glaciated areas in the Arctic and its melting could cause a significant increase in sea level rise. For this reason, the increased melting that has occurred on Linnébreen and other Svalbard glaciers due to the sediments trapped and entrenched on the glacier surface is a vital process to research and understand.

The research I conducted looked specifically at cryoconite holes on Linnébreen. It was my goal not only to understand how they evolved through time but also to see how they contributed to the melting of the glacier as a whole. In addition to the 6 cryoconite holes I made, I looked at three paired meter-by-meter plots; one where the surface was cleaned and scraped of all sediments and the other left in its natural state. This led to a qualitative observation: if the glacier surface had no sediments on its surface the melting process would

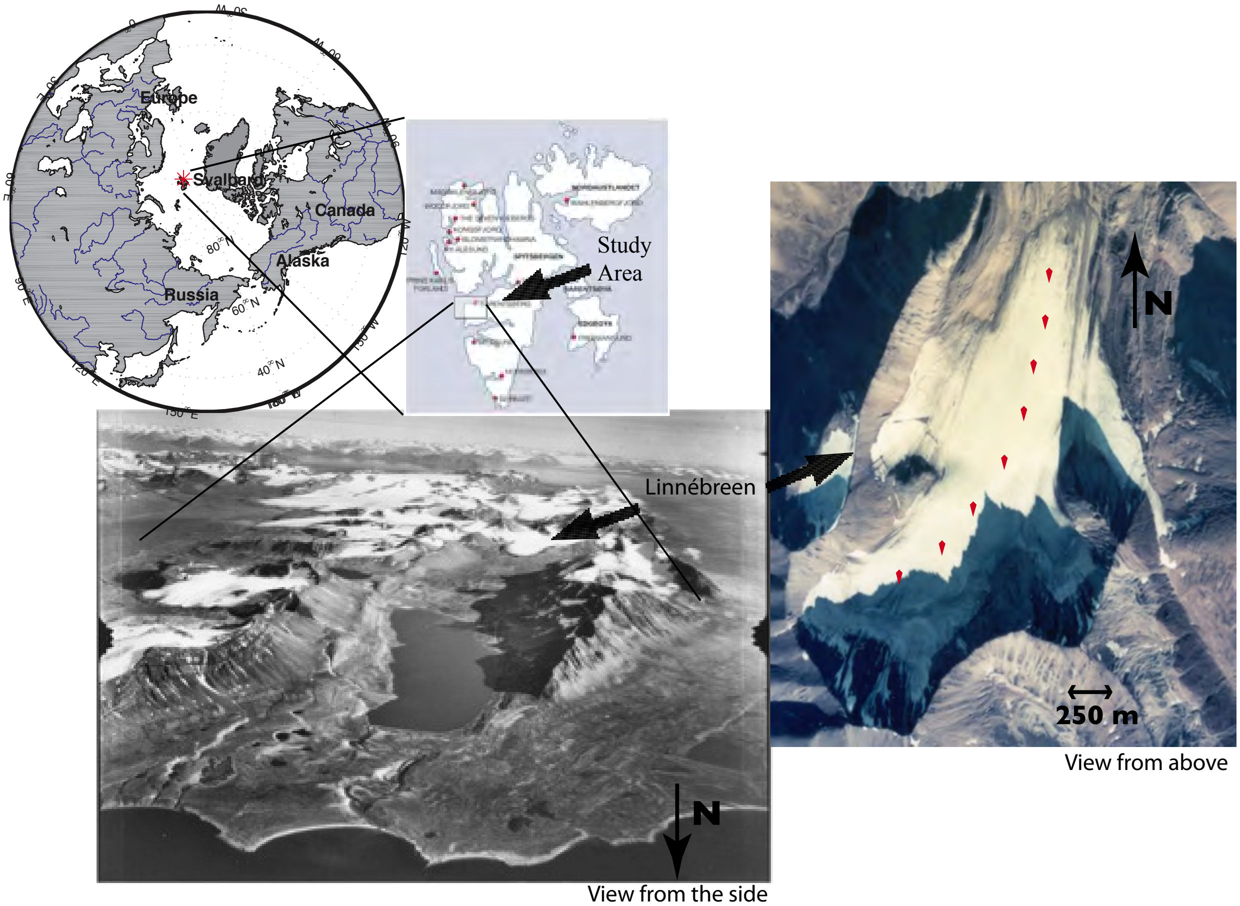

Figure 1.6: *Location of Field Site: Linnébreen. The aerial photo on the right was taken in 1995, where the red markers indicate the ablation stake locations.*

be slowed by nearly 27%. Thus it is (qualitatively at least) clear that the cryoconite can have a significant effect on the glacier melting process and perhaps even the surface melting.

Since little is known about the initial formation of cryoconite holes, I wanted to look at how different amounts of sediment eventually formed cryoconite holes. To do this, I collected sediments on the surface of the glacier and then distributed them in 6 adjacent piles, each increasing in size from 2.5 cm by 3.0 cm wide with a depth of 0.5 cm to 7.0 cm by 8.5 cm wide with a depth of 2.0 cm. I then monitored them for the next two weeks in order to see how they would grow and melt into the surface of the glacier.

I often noted that the surface of the glacier was riddled with very small streams that ran along the surface of the glacier and sometimes joined with others to form larger ones or eventually sink into the surface. The majority of these streams had sediment trapped along the bottom under the ice. This led to the question of whether cryoconite holes can lead to increased surface melting and small surface streams. I hoped that with my experiment of artificially creating my own cryoconite holes out of sediment collected on the surface of the glacier, I would be able to see if the cryoconite holes shifted around or began to collect water that might eventually run down the surface of the glacier.

Chapter 2

Data

At the beginning of the experimental period, July 28th, 2010, I set out six different sized, roughly circular sediment plots at the third ablation stake on the glacier, near the end of the ablation zone of the glacier (see Figure 1.6). The smallest hole had a radius of about 2.0 cm and a depth of 0.5 cm. The largest hole had a radius of about 7.0 cm and a depth of 2.0 cm (see Figure 2.5). The data was collected on Linnébreen over a period of fourteen days, from July 28th to August 10th, 2010. In general, each cryoconite hole was measured and photographed every other day. Occasionally, the field site was visited multiple days in a row. In addition to the cryoconite measurements, a weather station, at ablation stake three, collected data year round on the incoming solar radiation, liquid precipitation, air temperature, relative humidity, surface lowering, wind speed and direction.

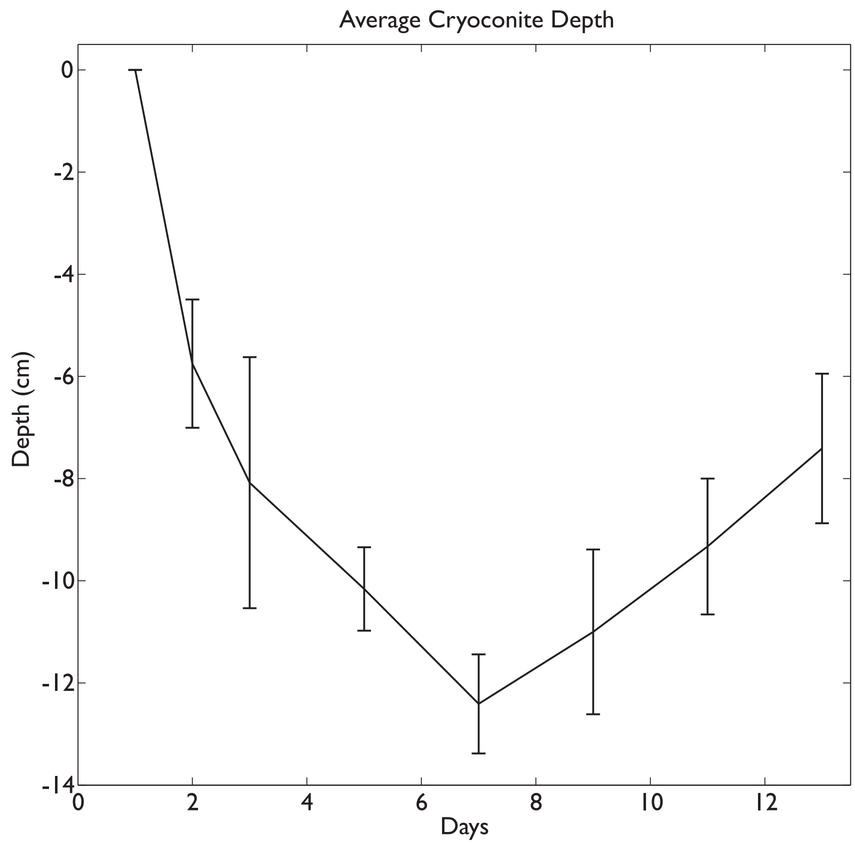

Figure 2.1: *This graph represents the average cryoconite depth measured over the two week observation period. Day 1 corresponds to July 28th, 2010 and Day 13 corresponds to August 9th, 2010. The error bars indicate the spread of the depth values measured for each cryoconite.*

In Figure 2.1 you can see the average cryoconite depth over the two week period. In general, the trend was rapid melting for the first week and then a return to the surface of the glacier for the second week. I hypothesize that this is due to the introduction of water into the system (see Figure 2.9). Once the water was introduced, ice would generally form over the hole at night, thus decreasing the melting. This pattern was also seen in Takeuchi's data (see Figure 1.5). In Takeuchi's data, the cryoconite holes increased in depth from July 28th, 1994 to August 3rd, 1994; the exact same time frame as my data. The cryoconite holes then rose to their original depth and fluctuated slightly around a depth of 4.5 cm. Unfortunately, for my experiment, data collection stopped on August 10th, so I cannot compare the data to the rest of Takeuchi's data; however, the trend supports a strong correlation between the trends seen on Linnébreen in Svalbard and Yala Glacier in Nepal.

While all six of the cryoconite increased in size (both radius and depth), the diameter of the largest cryoconite hole grew the most (see the photo progressions in Figures 2.5 to 2.13). It is unclear whether this was due to the radius of the hole or to the thickness of the sediment, since it was largest in both respects. However, given Brandt's results (see Figure 1.4) that showed a correlation between thickness of sediment and diameter, I would infer that the large diameter observed on Linnébreen was due to the thickness of the sediment. As the diameter increased, however, the sediments became increasingly spread out (again, refer to photographs in Figures 2.5 to 2.13) so that there was only a thin layer of sediment at the original placement and the thickest part of the sediment was further down glacier. This is most likely due to the hydrology of Linnébreen which during the month spent on the glacier always had some surface meltwater. On day three of the experiment, after a large rainfall, the cryoconite holes began to move down glacier and form slight pools of water beneath them (see Figure 2.7). This water eventually carried the majority of the sediment down glacier from the original position.

The breaking and movement of cryoconite holes was also noted on Yala Glacier in Nepal by Takeuchi et al.. He found that over 25 days, 13 of the 17 holes he measured "broke" and many of them "relocated". Like Takeuchi's site, my site was also surrounded by ice that was not entirely free of darker material and the albedo could easily change due to the relocation of material on the glacier. During the month spent on the glacier, I noted that many sediments would be relocated from day to day. The introduction of rainfall at the site definitely affected the final placement and size of the cryoconite holes. That is why this data correlates much better with the data from Takeuchi and Brandt, who both conducted their research in Nepal where rainfall is also a factor, and not with Fountain's data, who conducted his research on the dry Antarctic surface. Antarctica's cryoconite holes are very different because there is no surface melt and thus the cryoconite position and diameter does not change even during the summer. Furthermore, the shape is held constant on Antarctic glaciers because there is no transportation of sediments.

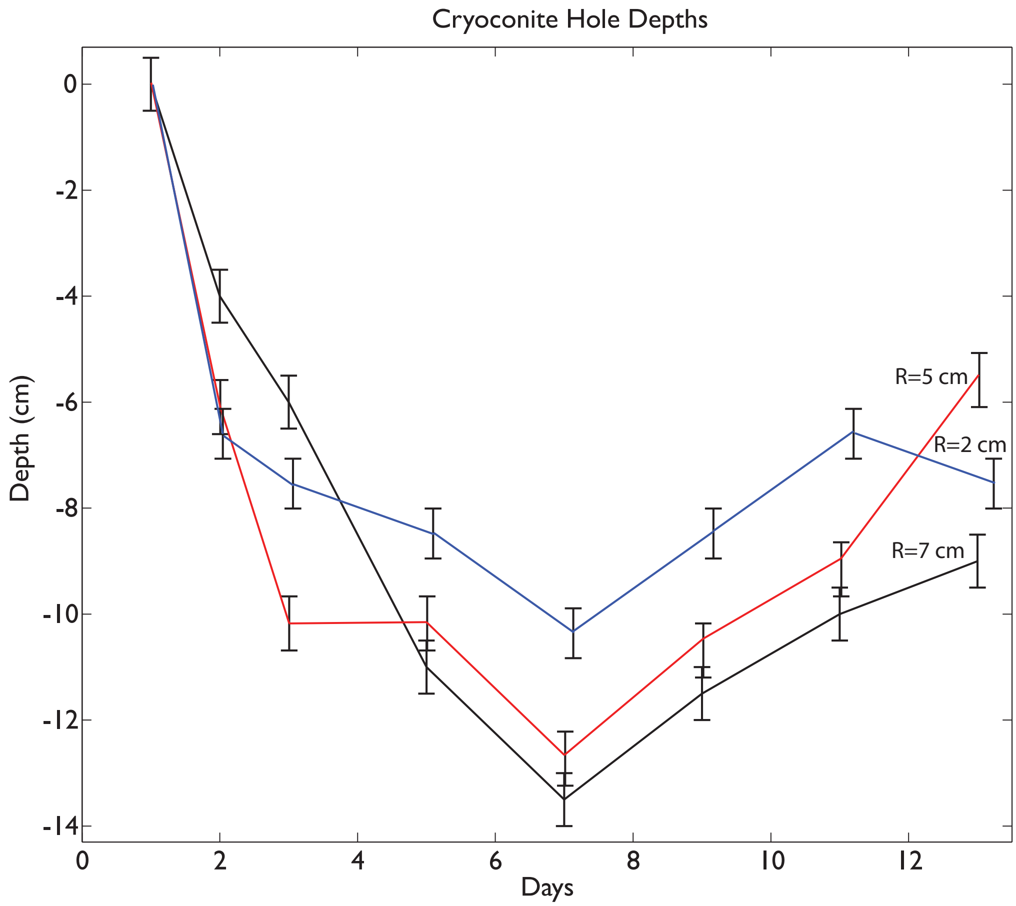

Figure 2.2: *This graph shows the plots of the depth changes for three of the cryoconite holes of different radii and their error bars. Day 1 corresponds to July 28th, 2010 and Day 13 corresponds to August 9th, 2010.*

While we can see that there is a general trend to the depth data, what about the individual holes? Figure 2.2 graphs three representative holes with radii ranging from 2 cm to 7 cm. As you can see, they all follow the general trend of increasing in depth for the first week and then decreasing in depth for the second week with a few variations. Most noticeably, the last measurement made with the hole of radius of 2 cm actually showed an increase in depth. This is most likely due to the fact that from day 11 to day 13, the sediment became more concentrated as it traveled down glacier; that, along with the increase in radius, probably enhanced its melting further into the glacier.

Figure 2.3 shows two of the holes' measurements plotted with the average cryoconite depth underneath it in a light gray line. The cryoconite with initial radius of 7 cm (shown with the red line) follows the average depth very well whereas the cryoconite with radius of

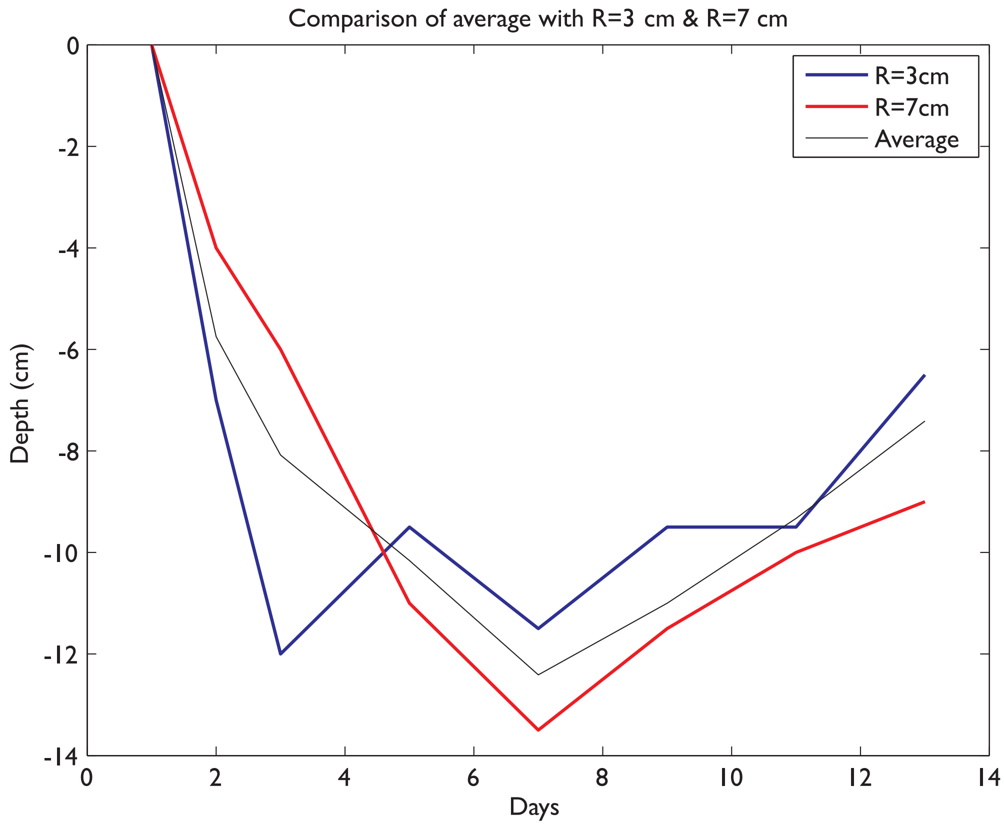

Figure 2.3: *This graph shows the depths recorded for each of the cryoconite holes formed. The dark black line represents the average of all of these depths (same as in Figure 2.1). Day 1 corresponds to July 28th, 2010 and Day 13 corresponds to August 9th, 2010.*

3 cm does not follow the average depth, especially at the beginning (shown with the blue line). For the hole with radius of 3 cm, its depth rapidly increases for the first three days but then proceeds to generally decrease in depth, with almost constant fluctuation with each measurement. The fluctations at the end are almost certainly due to the fact that the third cryoconite hole underwent the greatest change; a lot of the sediment from the second cryoconite hole combined with the third cryoconite hole as time progressed and the sediment movement caused greater transformation of the shape of that hole more than any of the others (see Figures 2.5 through 2.13) The initial large increase was most likely due to the fact that for the first three days the sediments stayed very concentrated and the shape of the third cryoconite hole was the flattest and most consistently round, perhaps causing more sunlight to reach it than the other holes and increasing the melting process.

The final graph (Figure 2.4) compares the amount the glacier surface ablated and the average depth of the cryoconite holes. Unlike the previous graphs, the values measured each

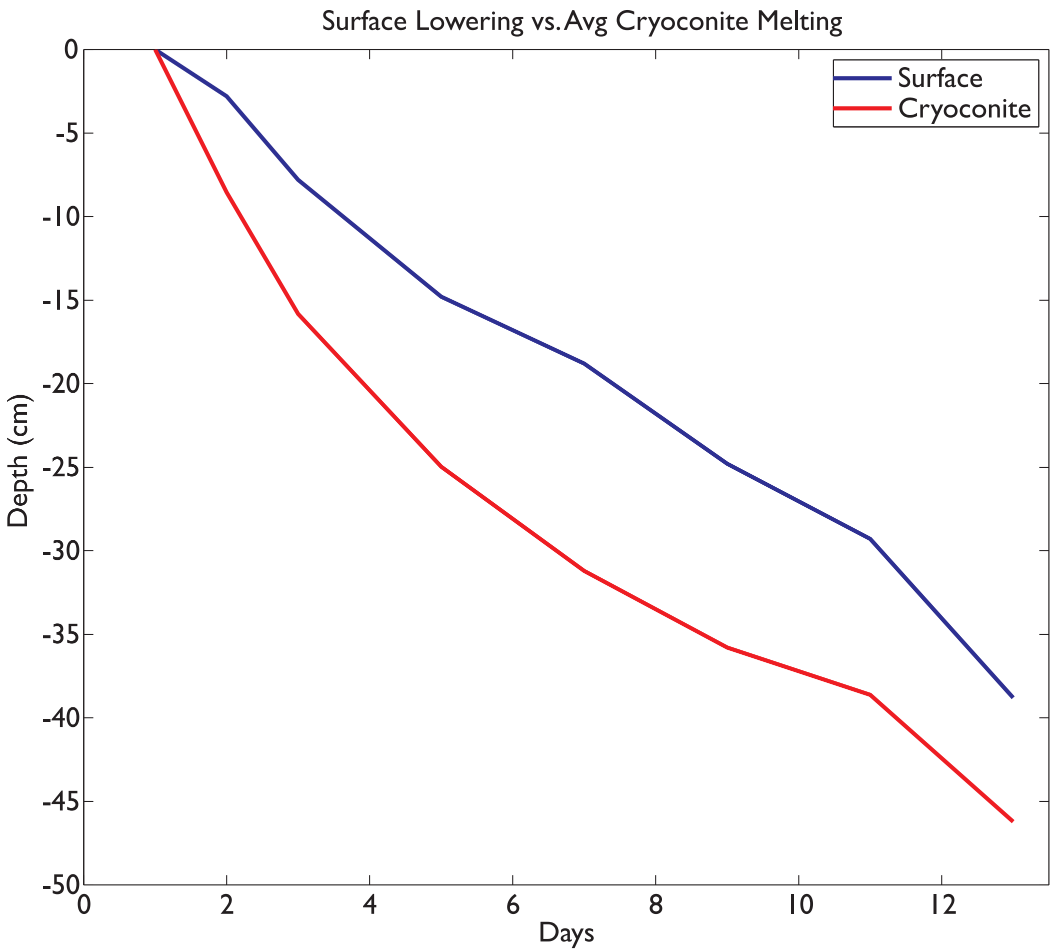

Figure 2.4: *This graph compares the amount the surface lowers each day and how far the average cryoconite surface is beneath the surface. Day 1 corresponds to July 28th, 2010 and Day 13 corresponds to August 9th, 2010.*

day were added to the previous days' depths. So for the third day, the value measured that day was added on to the depth increase from each previous day. The glacier surface lowering was calculated in the same way. For day one, the surface and the cryoconite are both on the surface (0), the following values are how far the surface and the cryoconite are from the *initial* surface it was placed on. Thus if you subtract the red line from the blue line you would get the depth beneath *that* day's surface or the values from Figure 2.1.

This graph shows how the cryoconite holes deepened much faster than the surface lowered for the first seven days. After that it starts to peter off and finally after day eleven it appears to keep pace with the surface, reaching it's "equilibrium depth". Presumably, the cryoconite holes would stay near this depth since if its depth decreased it would receive more sunlight and begin to melt more thus increasing its depth; and if its depth increased

Figure 2.5: *Cryoconite holes, day 1 (7/28/2010).*

Figure 2.6: *Cryoconite holes, day 2 (7/29/2010).*

it would receive less sunlight and would begin to melt less thus decreasing its depth. Hence it is called the "equilibrium depth," because it tends to stay there.

Figure 2.7: *Cryoconite holes, day 3 (7/30/2010).*

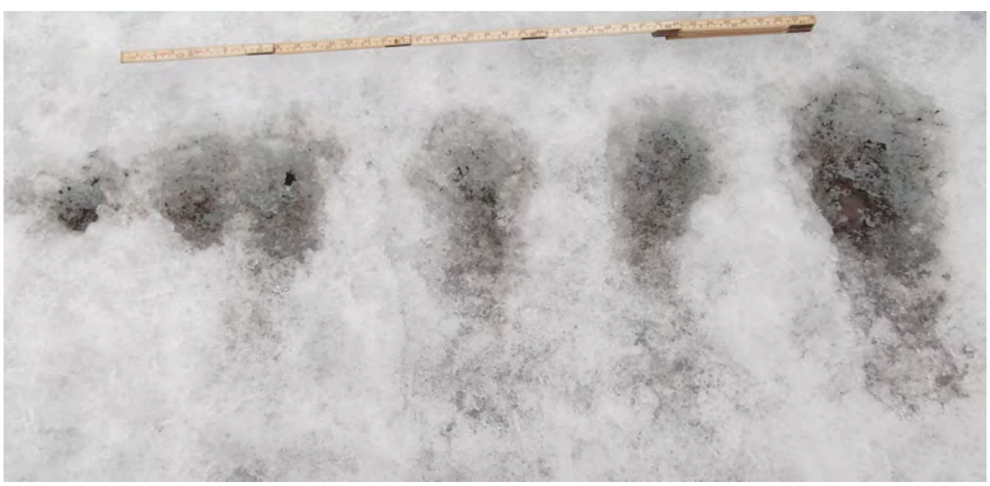

Figure 2.8: *Cryoconite holes, day 5 (8/1/2010).*

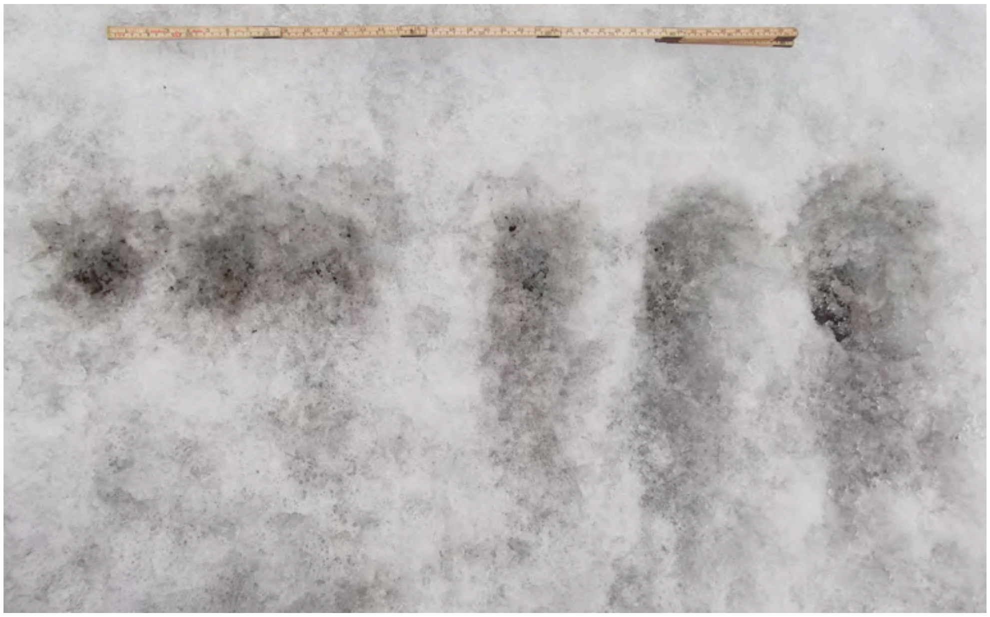

Figure 2.9: *Cryoconite holes, day 7 (8/3/2010).*

Figure 2.10: *Cryoconite holes, day 9 (8/5/2010).*

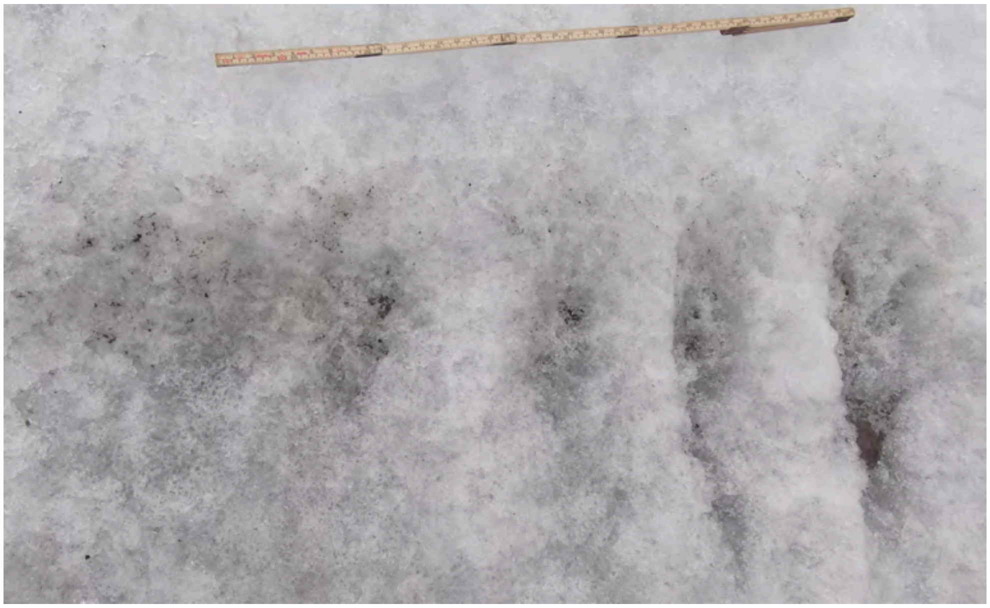

Figure 2.11: *Cryoconite holes, day 11 (8/7/2010).*

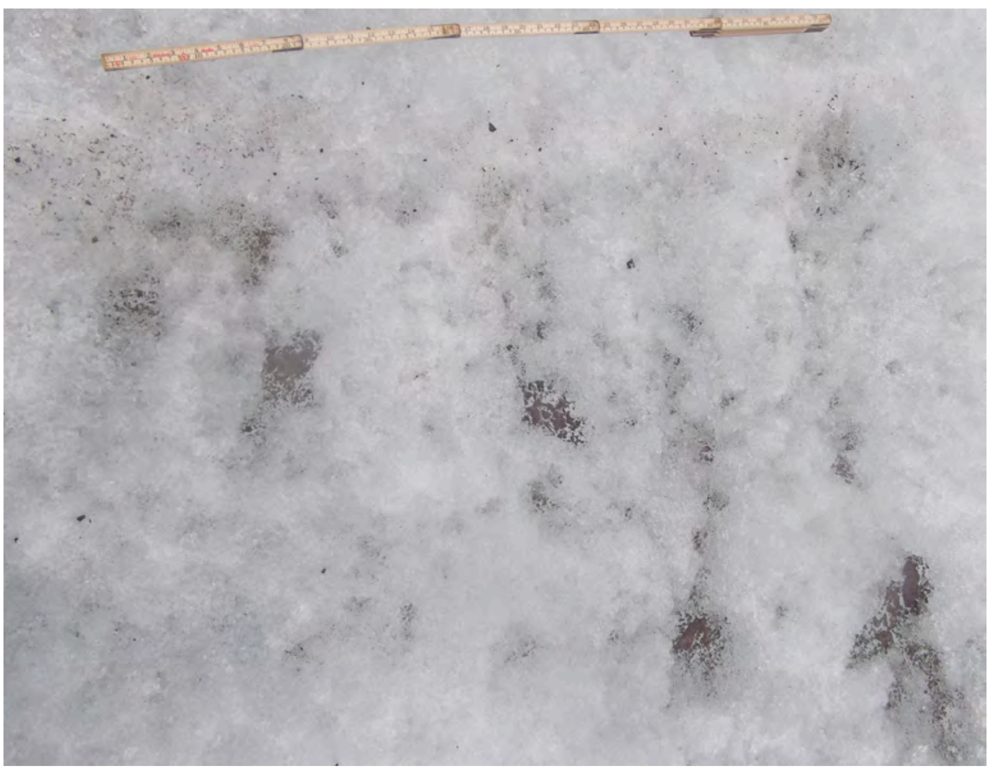

Figure 2.12: *Cryoconite holes, day 13 (8/9/2010).*

Figure 2.13: *Cryoconite holes, day 14 (8/10/2010).*

Chapter 3

The Model

3.0.4 Equations and Assumptions

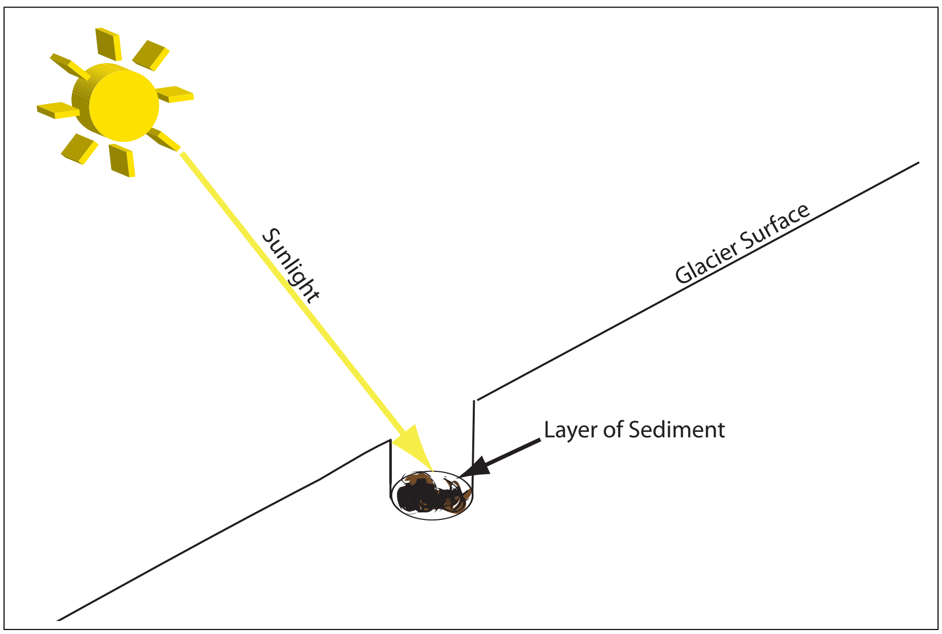

Figure 3.1: *The basic premise of the model: sunlight hits the layer of sediment, which, because of its lower albedo, preferentially melts into the surrounding glacier surface causing a cryoconite hole to form.*

The basic premise of the model created was to quantify the amount of ice the sediment would melt given the following parameters: the sun rotates around the site at a latitude of 77.9°N, 13.9°E and radiates 800 w/m^2 energy on average (given both the latitudinal position and the energy radiating off the water vapor, clouds and aerosols). The model also takes into

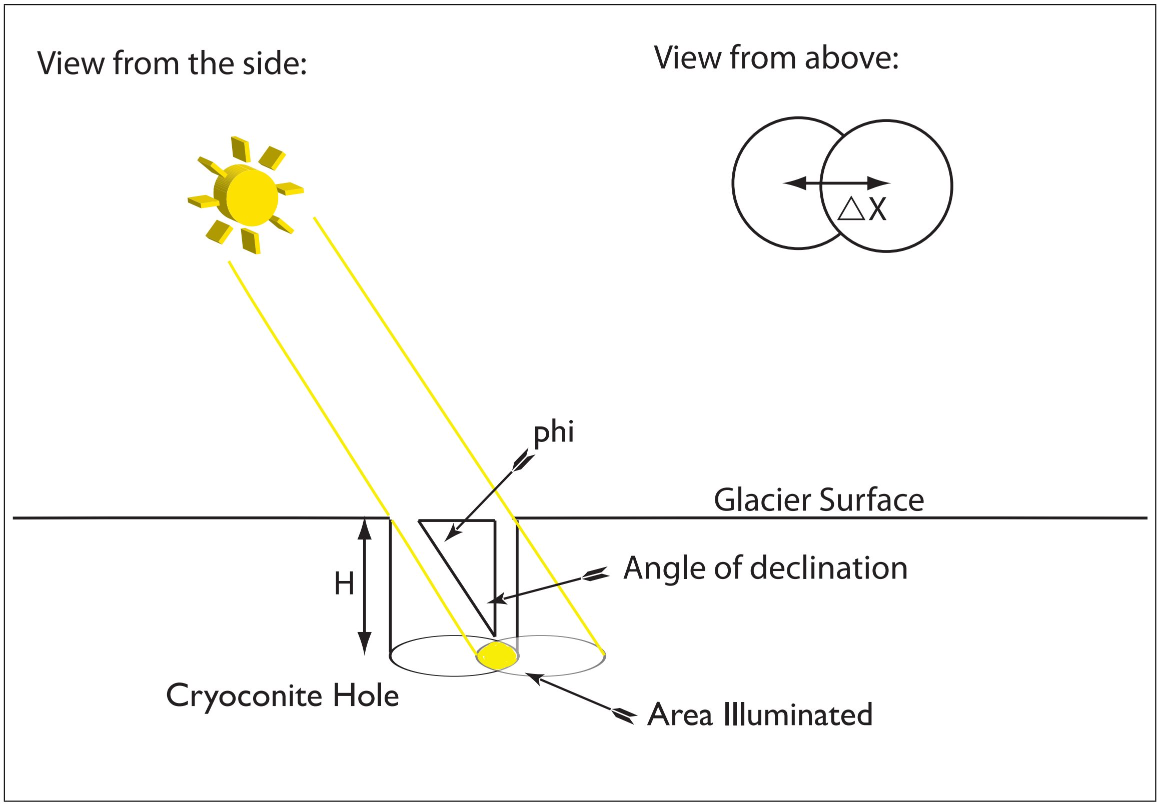

Figure 3.2: *This represents the first part of Phase I of the model where the sunlight directly hits only a section of the cryoconite hole (after it's partially melted into the glacier surface). In this part of the model we calculated the 'area illuminated' using the solar ephemeris to calculate the angle of incidence, φ.*

account the time of year. The radius of the cryoconite hole was assumed not to change at all, and the shape of the cryoconite hole was also assumed to remain the same throughout time (i.e. in the shape of a cylinder). We assumed that all of the sun's energy that made it to the surface of the sediment was used to heat and melt the ice beneath it (using the latent heat of melting value of 3.35×10^5 J/kg). However, in this model, none of the water generated from melting collected in the hole; instead it was assumed that it immediately traveled down the glacier. In actuality, the larger cryoconite holes did begin to collect water after about a week of melting. The final assumption was that there was nothing blocking the sunlight from hitting the glacier surface, which was likely untrue, especially during the spring and fall when the declination angle was low and the sun would be blocked for large periods of the day by the surrounding mountains. Also, during the summer, there were significant periods of cloudy weather where the solar radiation reaching the glacier surface was most likely lower. This also means we assumed that the glacier surface was flat (as depicted in Figure 3.2) while in actuality the glacier surface at the site was at an angle of $\sim 20°$ (see Figure 3.1).

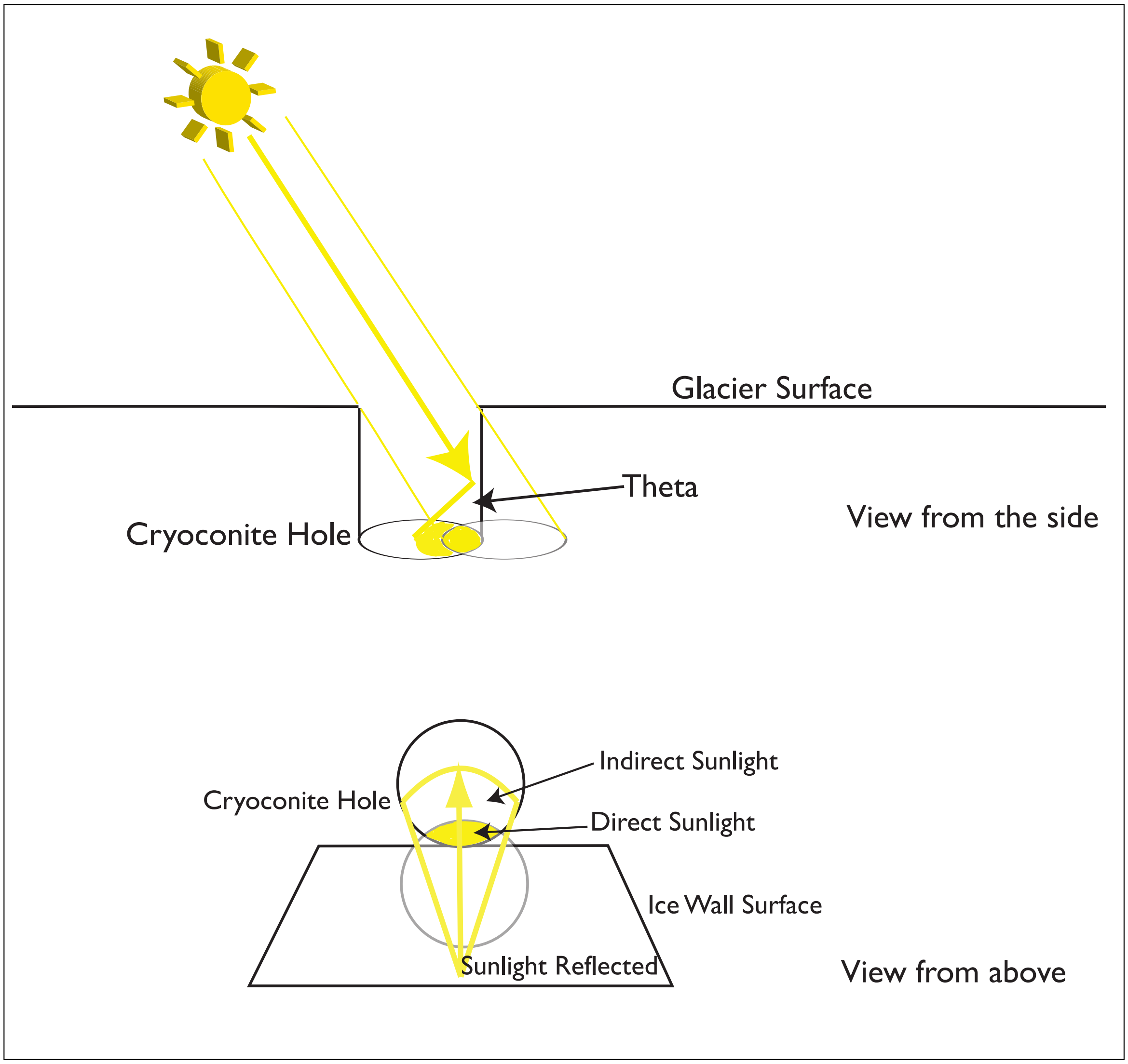

Figure 3.3: *This represents the second part of Phase I of the model where the sunlight directly hits a section of the cryoconite hole (after it's partially melted into the glacier surface) and sunlight is being reflected off the sides of the cryoconite hole and hitting the sediment on the bottom indirectly. In this part of the model we calculated the area that's indirectly illuminated using the angle θ as shown above.*

In Phase I of the model, there was some sunlight directly hitting the sediments at the bottom of the hole. This energy was calculated using the equation of the distance between the center of the two circles of the same radius (see Figure 3.2). So if the sun were directly above the hole, the radii would match up and the distance between the two centers of the circles would be zero, meaning that the energy that would melt the ice would be the full amount of the sun's energy that fell on the sediments. If the sun was at an angle (calculated using the hour angle and the angle of declination) then only part of the circles would overlap and the distance between the two centers would be greater than zero. In this case the area illuminated directly by the sun would only be a fraction of the incoming energy.

In addition to the sun directly hitting the sediments, some light would also hit the side of the hole which is composed of ice. Since ice has a high albedo, meaning it reflects a lot of the light hitting it, a lot of the energy would be reflected off the side the hole and be reflected away. In this model we assumed that the sunlight hitting the wall was all concentrated at one point (the middle point, see Figure 3.3) and using the angle it formed with the bottom of the hole, we calculated the fraction of the sunlight that was reflected onto the sediments. All of this sunlight was then turned into heat for melting the ice beneath it. We shall see the consequences of this assumption below.

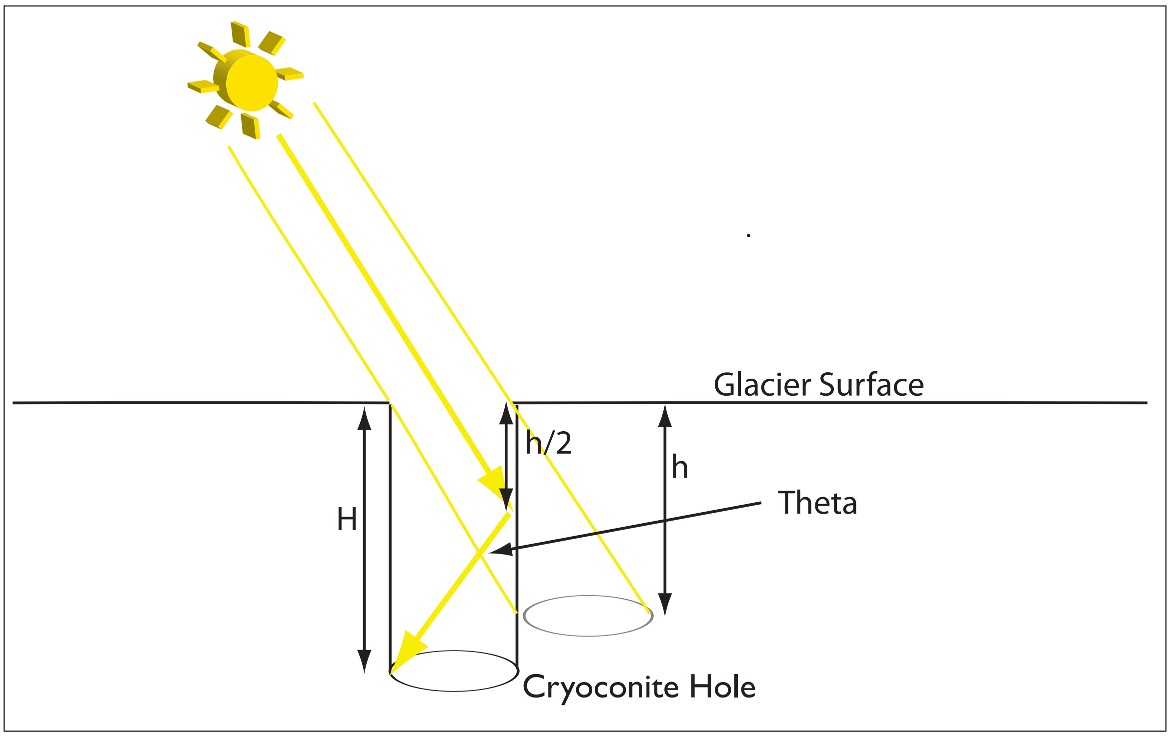

Figure 3.4: *This represents Phase II of the model where the sunlight no longer hits the cryoconite hole directly. All the energy reaching the cryoconite is through indirect reflection off the sides of the wall; calculated using the angle θ.*

In Phase II of the model, the cryoconite hole has become so deep that the sunlight can no longer directly hit the sediments at the bottom (the distance between the two radii of the circles is two times the radius). Instead, the only sunlight reaching the sediments is through indirectly reflecting off the side of the cryoconite wall (see Figure 3.4). In this part of the model we had to calculate the angle θ that the indirect sun's light formed when the ice sides reflected it (see Figure 3.4). Again, the sunlight was assumed to hit only one point on the side of the hole and we calculated the amount of light reflected using the angle theta.

We did not account for the amount of sunlight reflected to the other side of the hole, since we assumed that the shape of the hole was constant throughout time.

The hour angle of the sun's rotation was calculated using:

$$h = 2 \times \pi \times t.$$

The hour angle describes the position of a point on the celestial sphere. In this case, the hour angle of a point on the Earth's surface is the angle through which the earth would turn to bring the meridian of the point directly under the sun. Since the earth is rotating, the hour angle depends on t. In order to fully specify where the sun is in relation to a point on earth, the hour angle must be paired with the angle of declination of the sun (see Figure 3.2), which was calculated using:

$$dec = 23.45^\circ \times \sin(\tfrac{360}{365} \times (time + 284)).$$

The angle of declination gives us the energy of the sun hitting the surface of the earth, accounting for the differences due to latitude. Next the angle ϕ (see Figure 3.2), the angle that the sunlight hits the bottom of the cryoconite hole, was calculated using the angle of declination, the hour angle of the sun and the latitudinal position of the site:

$$\phi(t) = \arcsin(\cos(h) \times \cos(dec) \times \cos(lat) + \sin(dec) \times \sin(lat)).$$

The distance between the centers of the two circles (ΔX), one formed by the sun, the other the radius of the cryoconite hole, was calculated using ϕ, where H(t) is the height of the cryoconite wall changing with time:

$$\Delta X(t) = H(t) \times \tan(\phi(t)).$$

Here, ΔX will always be between 0 and 2R, where R is the radius of the circle. If ΔX is 0 then the circles are directly above each other and the sediment receives the full amount of solar radiation. If ΔX is 2R then the circles do not overlap at all and the sediment receives no direct radiation. Using ϕ(t) and ΔX(t), the area of illumination (i.e. the area of overlap) (see Figure 3.2) was determined using the following equation:

$$A_{illum}(t) = (\phi(n) \times 2 \times R^2 \times \arccos(\tfrac{\Delta X(t)}{2R}) - \tfrac{1}{2} \times \Delta X(t) \times \sqrt{4 \times R^2 \Delta X(t)^2}$$

where n is: $0^\circ < n < 90^\circ$. Once the illuminated area was calculated, then the amount of energy directly hitting the surface of the sediments could be calculated using:

$$E(t)_{direct} = I_0 \times \cos(\phi(t) \times A_{illum}(t) \times (1 - \alpha_{dirt})$$

where $E(t)_{direct}$ is the the amount of energy directly hitting the surface, I_0 is the solar radiation constant (= 800 W/m^2), and α_{dirt} is the albedo of the dirt. Next, the indirect energy was calculated:

$$E(t)_{indirect} = I_0 \times \cos(\phi(t)) \times (\pi \times R^2 - A_{illum}(t) \times \tfrac{\theta(t)}{2\pi} \times \alpha_{ice} \times (1 - \alpha_{dirt})$$

where $E(t)_{indirect}$ is the amount of energy being reflected off the the sides of the hole and onto the sediment at the bottom; θ is the angle the reflected light makes with the surface of the wall; and α_{ice} is the albedo of the ice. From $E(t)_{direct}$ and $E(t)_{indirect}$, the amount the ice melted (i.e. the change in height of the hole) could be calculated using the latent heat of melting, L = 3.35 $\times 10^5$ J/kg and the density of ice, ρ = 917 kg/m^3:

$$dh = \frac{(E(t)_{direct} + E(t)_{indirect})dt}{\rho \pi L}$$

where dh is the change in height of the wall and dt is the change in time. This equation gives us the change in depth caused by Phase I of the model. For Phase II, the only light is indirect and the equation looks very similar:

$$E(t)_{indirect} = I_0 \cos(\phi(t))\pi R^2 \times \frac{\theta}{2\pi} \times \alpha_{ice} \times (1 - \alpha_{dirt}).$$

This equation only had an effect when the following parameters were satisfied ϕ <90 and A_{illum}=0. Thus when Phase II caused melting, Phase I would not cause melting (because the indirect radiation was already being calculated by Phase II). The change in height was calculated using:

$$dh = \frac{E(t)_{indirect} dt}{\rho \pi L}.$$

Putting this together with the dh from Phase I, gives us the complete model and the calculated depth of cryoconite holes.

Once I completed the change in height of the cryoconite holes, I added one final section which was the glacier surface melting. For this part I calculated the height change of the glacier surface and then added that height change to the depth change of the cryoconite. The equation I used to calculate the amount of glacier surface change is very similar to the one used to calculate the change of cryoconite depth:

$$E_{glacier} = I_0 \times \cos(\phi(n)) \times (1 - \alpha_{ice0)}$$

where $E_{glacier}$ is the energy of the sun that hits the glacier surface. Once the energy part was calculated, then the height change was calculated using:

$$dh_{glacier} = \frac{E_{glacier}(t)dt}{\rho L}.$$

This gave us the change in height of the glacier surface which we could then add on to the change in depth of the cryoconite hole.

3.0.5 Model Results

Once the model was created, it was tested by changing certain parameters while holding the others constant to see how the melting process would change with that variable. I tested four parameters: the radius of the hole, the albedo of the ice, the albedo of the dirt, and the time of year. Changing the radius of the hole was by far the biggest factor in

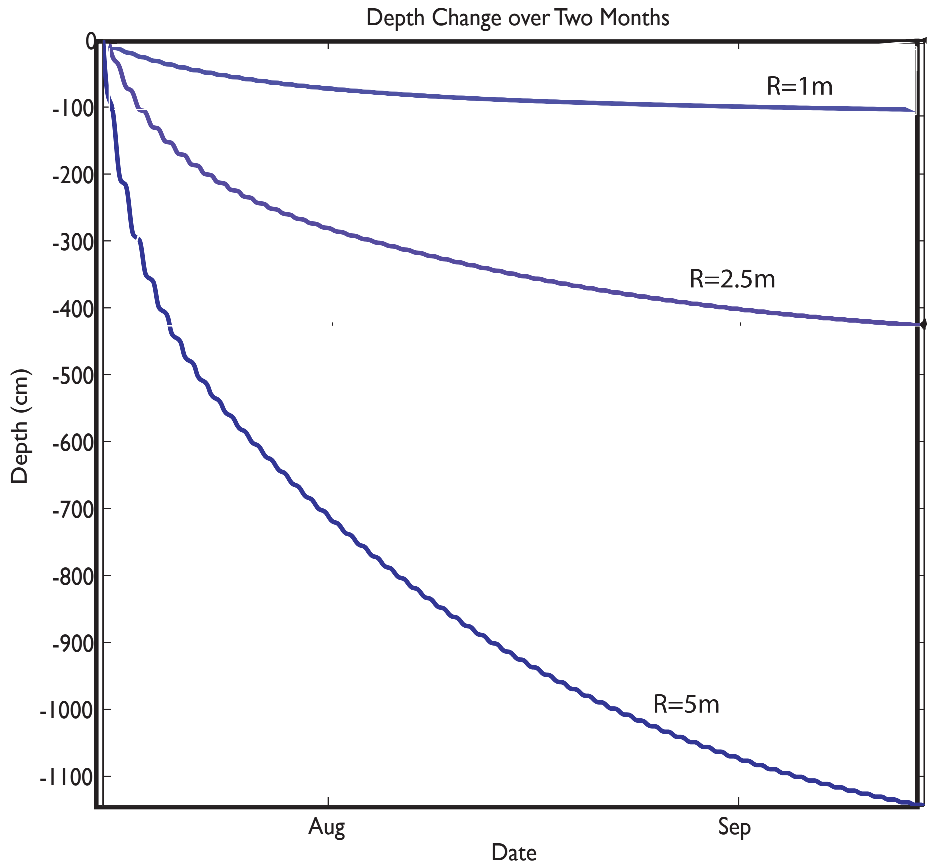

Figure 3.5: *This graph was created using the model described earlier where the radius changes from 5m to 2.5m to 1m keeping the albedo of the ice constant at 0.6 and the albedo of the dirt constant at 0.15. The lines represent the increasing depth over a period of two months at the end of the 2010 summer.*

how far the cryoconite hole would melt into the glacier. In Figure 3.5 you can see how a hole with radius of 1m melted a meter into the glacier over the period of two months while a hole with radius of 5 m melted over 10 m into the glacier and looks like it would continue melting if sunlight continued to be present. This makes sense, given the parameters of the model: the larger the hole, the longer the bottom of the hole will be hit by direct sunlight. Also, the larger the hole is, the more indirect sunlight hits the bottom of the hole.

In the next run of the model I put in the initial radii of the cryoconite holes that I formed (Figure 3.6). I started with my second smallest cryoconite hole with a radius of 0.03 m to my largest cryoconite hole that started with a radius of 0.07 m. In Figure 3.6 you can see that a change of 1 cm can make a difference with how far the cryoconite hole

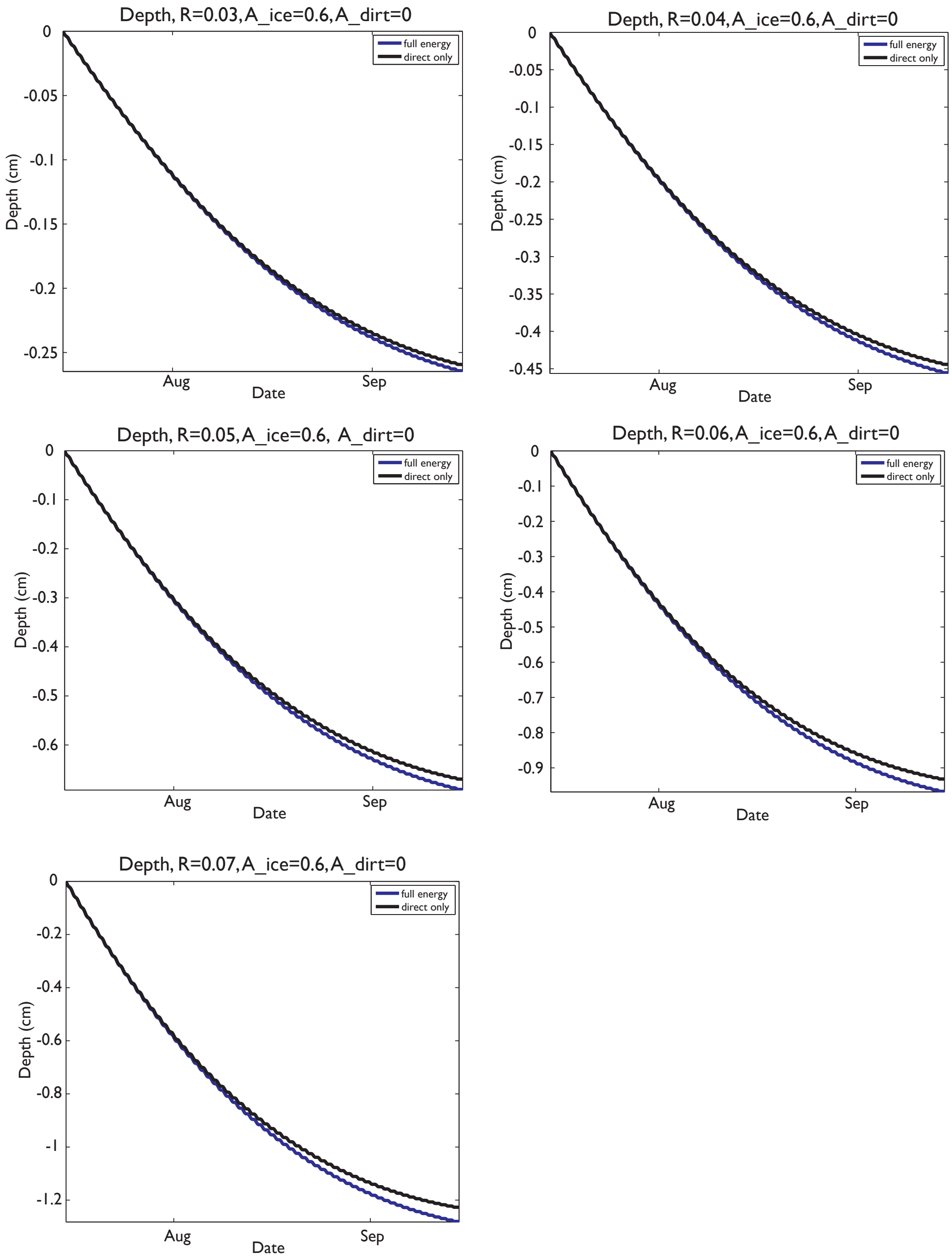

Figure 3.6: *These graphs were created using the model and show how the five different cryoconite holes I initially formed would have melted under the model's parameters over a period of 2 months from July 28th to September 28th. In each graph there are separate lines showing how the direct sunlight compares to the indirect sunlight (or full energy).*

melts into the glacier surface. The smaller the radius, the more an increase in radius affected the depth the hole would melt to. When the radius went from 3 cm to 4 cm, the final depth went from 2.5 mm to 4.5 mm, nearly double the depth; but when the radius when from 6 cm to 7 cm, the depth increased from 9 mm to 12 mm, only a third larger. Regardless of the radius, however, the depth that these modeled holes melted into the glacier surface is inconsequential to the data actually measured over the two week period. Even the hole with radius of 0.07 m only melted into the glacier by 1.2 cm, only a tenth of what was actually measured on the glacier. This is probably due to the fact that the radii of the actual cryoconite holes expanded over the course of two weeks. The largest hole went from a radius of 7 cm to 1 m; and in the model results, a modeled cryoconite hole with radius of 1 m melted 1 m into the glacier over a period of 2 months.

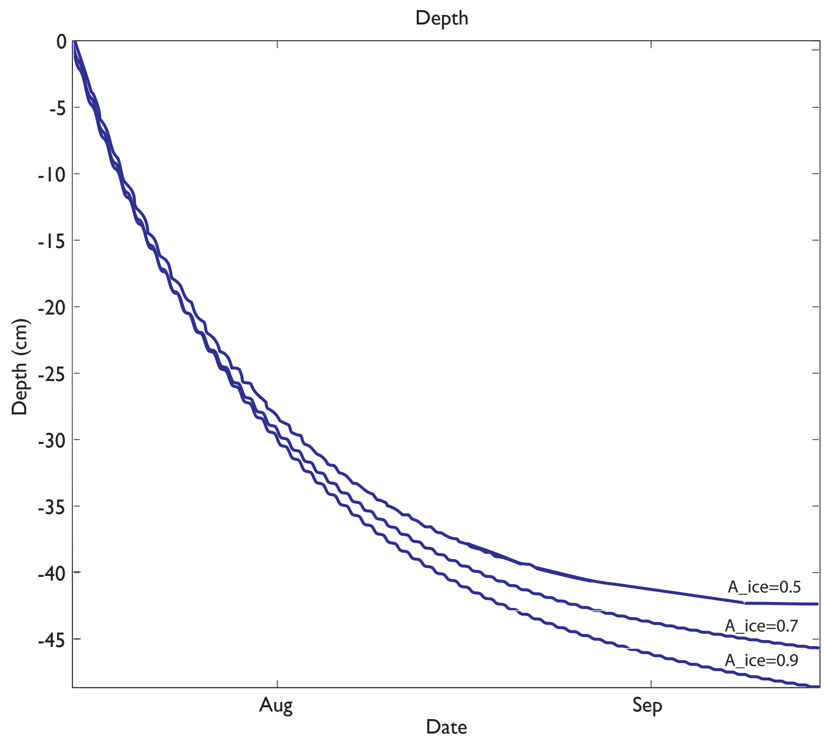

Figure 3.7: *This graph shows how the depth changes when you only change the albedo of the ice over a two month period. Albedo of the dirt was held constant at 0 and the radius of the hole was held constant at 0.7 m.*

Once I looked at what happened to the melting rate when I changed the radii of the holes, I then looked at how changes in the albedo of the ice could affect the melting of the holes. While changing α_{ice}, I kept the radius constant at 0.7 m and α_{dirt} constant at 0. Unlike the radius, changing α_{ice} did not affect the final depth as much. A change in α_{ice} of 0.4 only resulted in a 5 cm increase in depth. Instead, changing α_{ice} resulted in large differences in how much the hole melted due to the direct and indirect sunlight, which

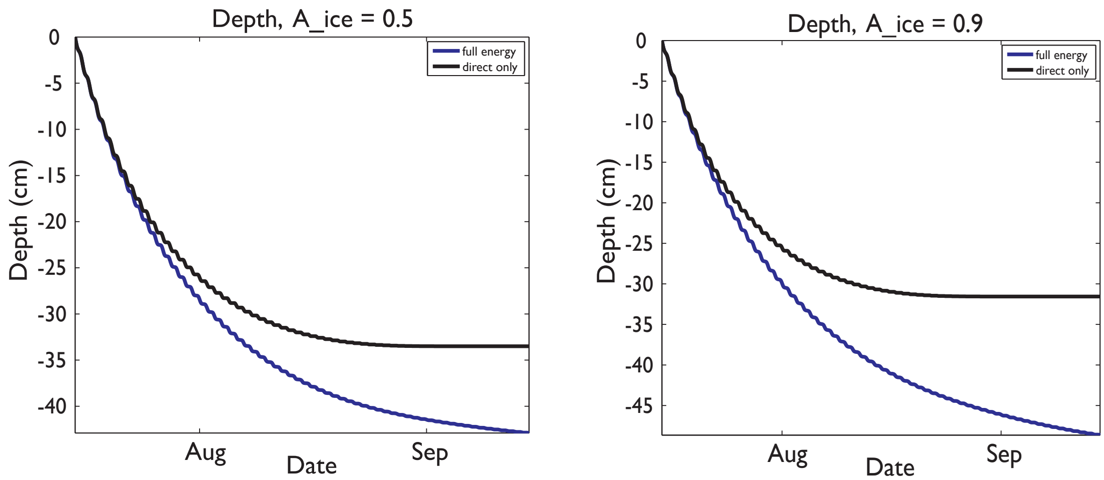

Figure 3.8: *This graph shows how the direct and indirect melting compare with two different albedos, 0.5 and 0.9. Albedo of the dirt was held constant at 0 and the radius of the hole was held constant at 0.7 m.*

makes sense given that the albedo of the ice causes all of the indirect melting (see Figure 3.8). When the albedo of the ice is 0.9, the change in depth from the direct light and the indirect light is over 15 cm; compared to when the albedo of the ice is 0.5 the change in depth from the direct light versus the indirect light is only 10 cm.

After changing the radii of the holes and the albedo of the ice, I next looked at what happens to the melting process when the abledo of the dirt is changed. Figure 3.9 shows different model runs with three different dirt albedos ranging from 0.1 to 0.5. The radius was held constant at 0.7 m and the albedo of the ice was held constant at 0.6. Clearly, the lower the albedo of the dirt, the more the cryoconite hole will deepen. If the dirt is reflecting less of the sun's energy then more of the energy will be converted into heat that will melt the ice beneath it. The larger albedo, the less the hole deepens. In this model, a dirt albedo of 0.1 melted the hole more than 40 cm into the glacier surface whereas a dirt albedo of 0.5 only melted the hole 30 cm into the glacier surface.

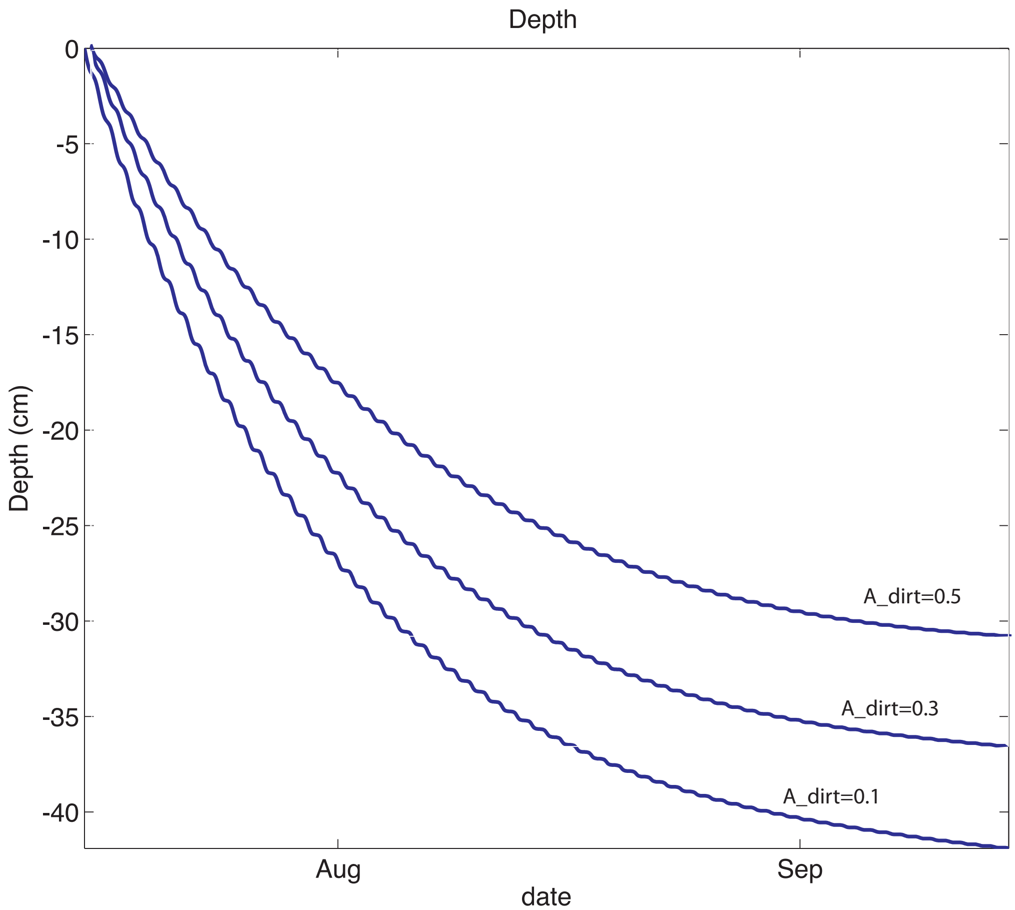

Figure 3.9: *This graph shows what happens when only the albedo of the dirt parameter changes in the model over a two month period. Albedo of the ice was held constant at 0.6 and the radius of the hole was held constant at 0.7 m.*

In addition to changing some of the parameters, I also looked at how much a cryoconite hole with a radius of 45 cm would melt into the glacier if it were only there for a day. I looked at four different times of year, July 28th, September 28th, December 28th and March 28th. In Figure 3.10 you can see that a hole placed on the glacier in the summer melts constantly throughout the day, but fastest at the beginning and end of the day. In Figure 3.11, you can see what happens to the depth when there is only sunlight during part of the day (on a spring day). In the winter, there is no change in depth over time because there is no sunlight present. These results make sense when you look at the solar declination, zenith angle and hour angle of the sun in combination with ΔX, A_{illum} and θ (see Figures 3.12 and 3.13). With these you can see that on a July day, almost the entire sediment surface is illuminated for 24 hours and ΔX remains very small. On a March day, the sun is much lower in the sky (see solar declination graph in Figure 3.14) and it goes below the horizon for several hours (see zenith angle graph in Figure 3.14). Thus for about

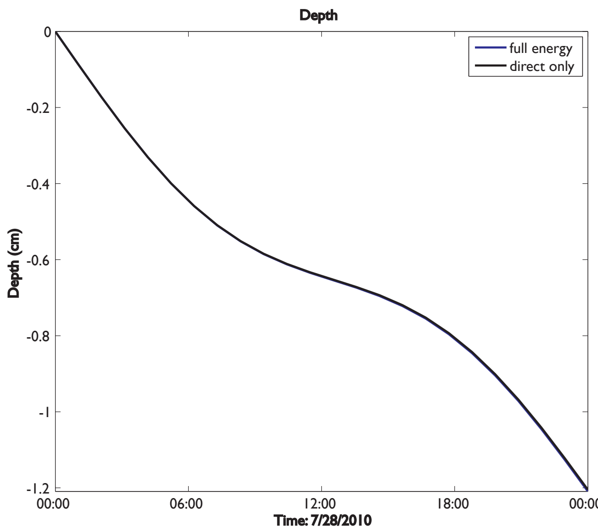

Figure 3.10: *This graph shows what happens to the depth of the hole when sediment with radius 45 cm is placed on the glacier surface for 24 hours on July 28^{th}.*

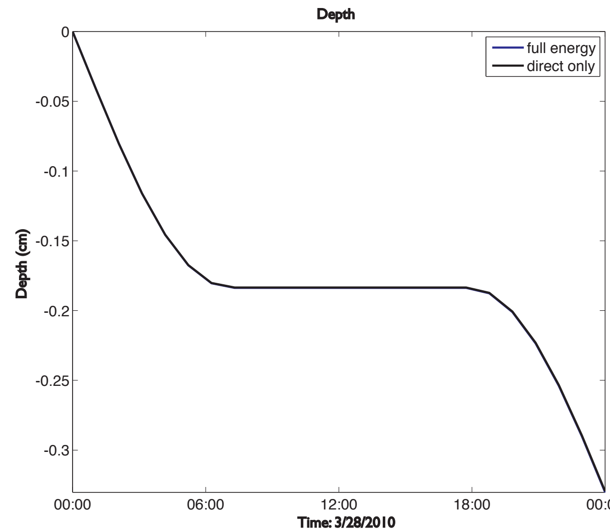

Figure 3.11: *This graph shows what happens to the depth of the hole when sediment with radius 45 cm is placed on the glacier surface for 24 hours on March 28^{th}.*

12 hours, there is no solar radiation directly or indirectly hitting the sediments (see the area illuminated graph in Figure 3.15) which leads to the graph in Figure 3.11 where the depth stops decreasing in the middle of the day.

One major problem with the model is that as long as there is sunlight present, the hole will continue to melt. In the real world, the hole would eventually reach a depth where such minimal sunlight would hit the bottom (either directly or indirectly) that growth of the hole would plateau and the hole depth would keep pace with the melting of the glacier surface. This is exactly what we see both in our data and previous research (e.g. Fountain et. al.). This model error is illustrated in Figure 3.16 where the model was run for two years, with a hole of radius 0.05 m, the albedo of ice at 0.6 and the albedo of the dirt at 0. Since a fraction of the sunlight hitting the side of the wall is assumed to be reflected to the bottom of the hole, no matter how deep the hole, sunlight is assumed to reach it and contribute to increased melting.

After testing out the effects different parameters had on the model, I also tried to fit the model output to the data collected. Figure 3.17 shows the best fitting curve given the dates of the original experiment (7/28/2010 to 8/10/2010), the measured albedo of the dirt (0.15) and the assumed albedo of ice (0.6). The radius that produced this data was 45 cm, which is not far from the average radius of the largest cryoconite hole since it continued to expand during the two-week observation period. However, although it reached the final depth of the cryoconite actually measured, it does not show the same pattern that all of

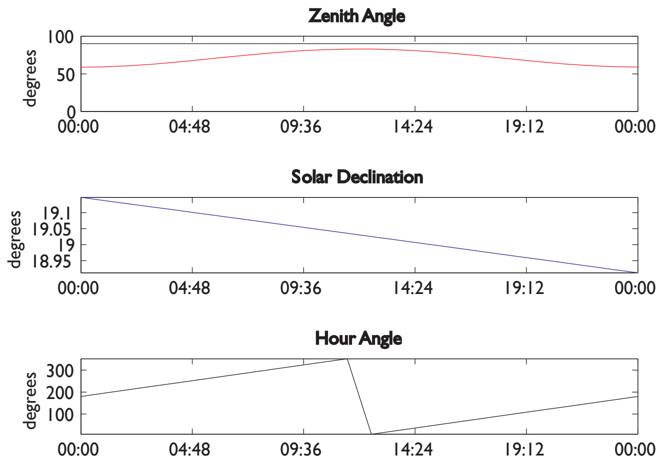

Figure 3.12: *These graphs represent parameters of the model: zenith angle, solar declination, and hour angle during one 24 hour period with a hole of radius 45 cm, July 28th.*

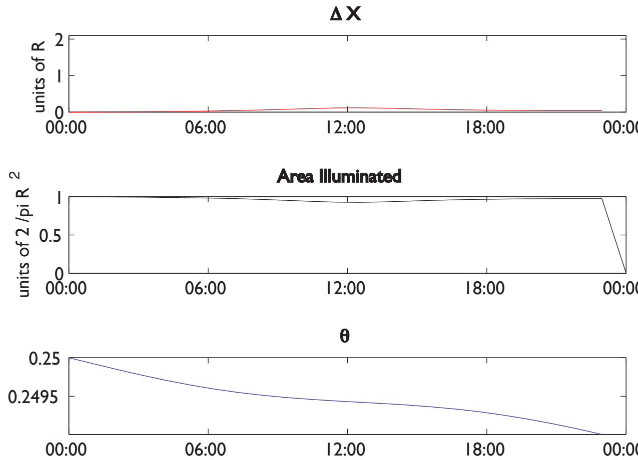

Figure 3.13: *These graphs represent parameters of the model: ΔX, A_{illum}, and θ during one 24 hour period with a hole of radius 45 cm, July 28th.*

the cryoconite holes displayed. Instead of increasing in depth for the first week and decreasing in depth for the second week, this model shows a constant increase in depth over the entire two week period. This, again, is due to two of the assumptions of the model: the fact that any sunlight present will continue to make its way to the cryoconite surface, regardless of how deep it is. And the assumption that the hole will convert that sunlight into energy to melt the ice beneath it means that the hole will continue to increase its depth no matter how deep it has moved into the glacier. Most importantly, though, is the assumption that no water collects in the hole, thus the albedo of the cryoconite remains constant throughout time.

One thing to note is that there are daily fluctuations observed. Each day there is a time when the melting goes faster than another part of the day. These "wiggles" increase as time goes on and this is due to the fact that as the summer drew to an end, the ephemeris angle grew smaller and smaller and the amount of sunlight reaching the cryoconite decreased. You can also see an increasing separation between the melting due to the direct sunlight and the full energy hitting the cryoconite. This is due to the increase in height of the cryoconite "wall." The taller the wall, the less direct solar radiation reached the cryoconite surface and the more the melting was due to the sunlight being reflected off the walls of the hole.

I also ran the actual measured parameters into the model which produced figure 3.18. In this run of the model, the radius was 7 cm (the largest cryoconite formed), α_{ice} was 0.45

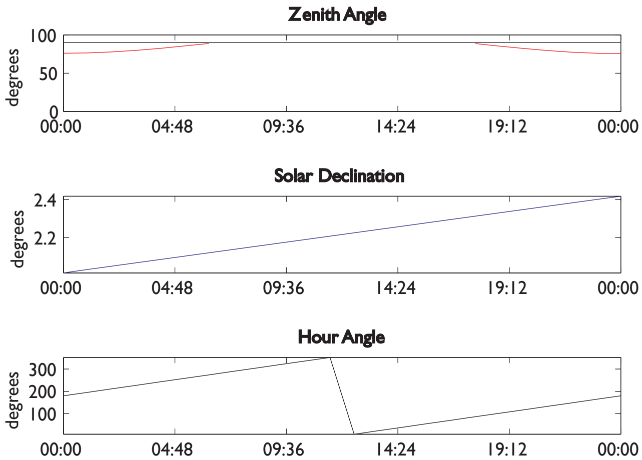

Figure 3.14: *These graphs represent parameters of the model, zenith angle, solar declination, and hour angle during one 24 hour period with a hole of radius 45 cm, July 28th.*

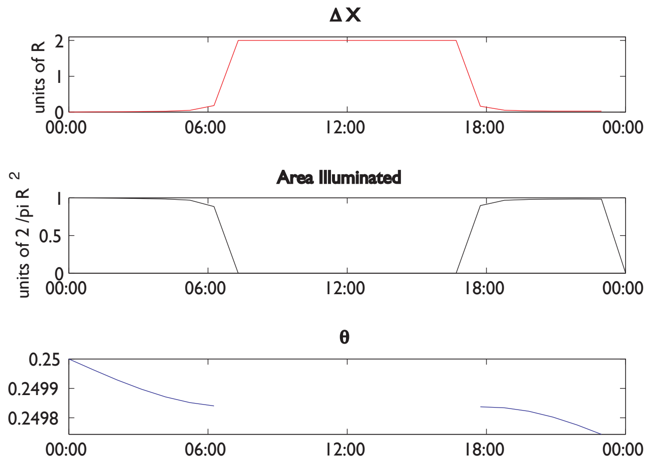

Figure 3.15: *These graphs represent parameters of the model,* ΔX*,* A_{illum} *and* θ *during one 24 hour period with a hole of radius 45 cm, March 28th.*

(a value measured in the field), α_{dirt} was 0.45 (again, a value measured in the field) and the dates were set to the dates I actually took measurements in the field (July 28^{th} to August 10^{th}, 2010). Here we can see that by the end of the two week period, the hole only melted 3 mm into the glacier and there is almost no difference between the amount of melting due to indirect light versus direct light. This is due to the fact that the hole did not melt far into the glacier; since it was near the surface the whole time most of the light reaching it *was* direct light. The reason the hole does not melt very far into the glacier in this model is most likely due to the fact that the radius of the hole stayed constant throughout time. When I actually collected the data, the radius continued to increase and the sediments moved around. In the model, neither of these things were taken into account. Thus, with such a small radius, the sediment would not produce enough heat to melt the ice beneath it.

Finally, I included the glacier surface melting into the model (see Figure 3.19). In this figure I have three lines. The black line shows how far the cryoconite melts beneath the surface due to the direct energy its received. The purple line shows how far the cryoconite melts beneath the surface due to all of the energy that it receives (both directly and indirectly from the reflected light). And the red line shows how far the glacier surface melts over the course of two months from July 28^{th}, 2010 to September 28^{th}, 2010. In this run of the model, α_{dirt} is 0.15, α_{ice} is 0.6 and the radius is 45 cm. It is important to compare this graph to the graph in Figure 3.17 since they have the same parameters but instead of showing the depth from the *initial* glacier surface it was placed on, it shows the depth

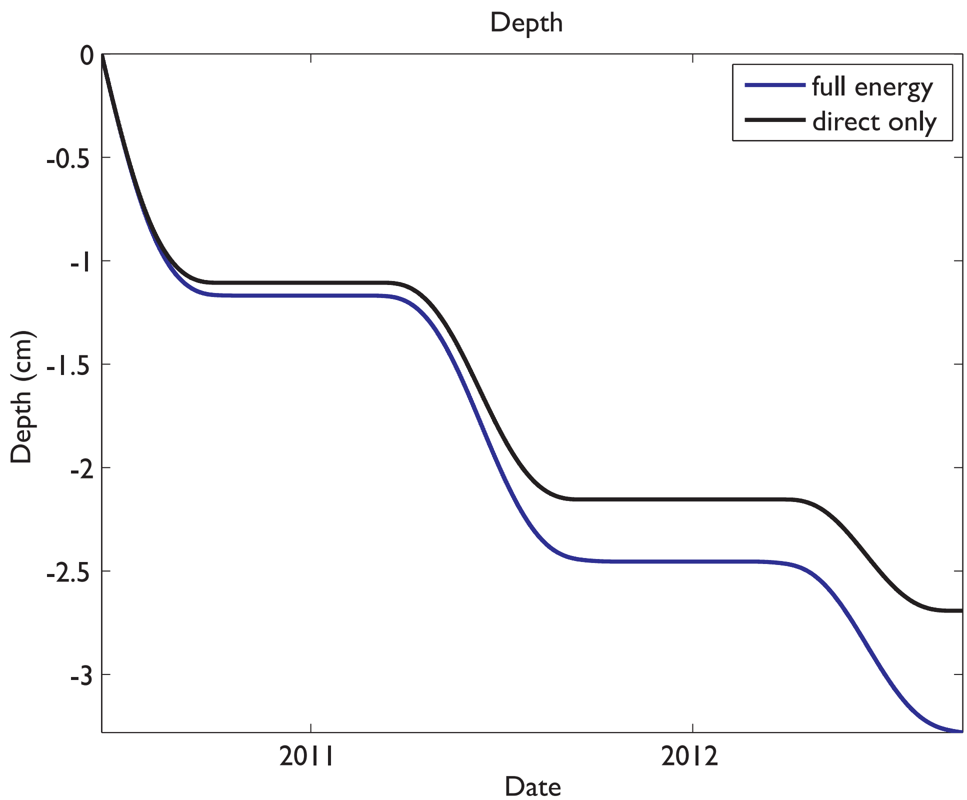

Figure 3.16: *This graph shows how a cryoconite hole with radius of 5cm, a dirt albedo of 0 and ice albedo of 0.6 would melt over a period of two years.*

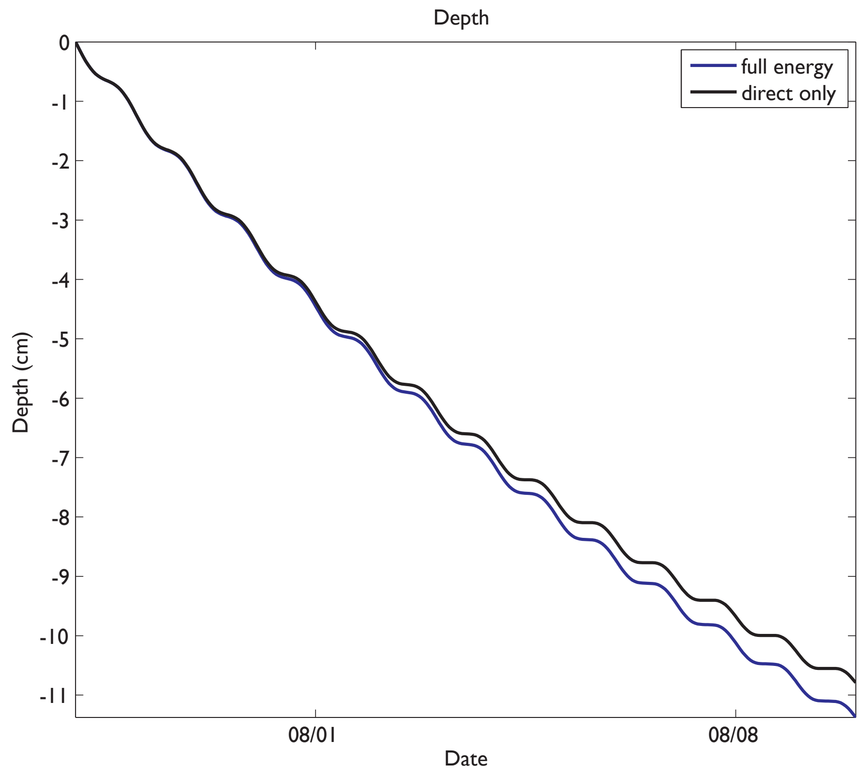

Figure 3.17: *This graph represents the parameters that most closely 'fit' the data actually collected. The dates are kept the same as the actual dates. The albedo of ice was set at 0.6, the albedo of the dirt was set at 0.15 and the radius of the hole was set at 45cm.*

measured each day (while ignoring the fact that the surface is melting as well). So if you subtract the purple line from the red line you get the values shown in Figure 3.17.

This graph also functions as the model equivalent of the data collected, shown in Figure 2.4. Interestingly, the glacier surface in the model melts at about the same speed as the measurements made on Linnébreen. From July 28$^{\text{th}}$ to August 10$^{\text{th}}$ the glacier surface melts about 40 cm, whereas the Linnébreen surface melted about 45 cm during that same time frame. The biggest difference seen when comparing these graphs is that the distance between the glacier surface and the cryoconite surface is always increasing in the model, whereas for the actual data the cryoconite depth eventually plateaus, keeping pace with the glacier surface once it has reached the "equilibrium depth". Again, this is due to the fact that no matter how much sunlight there is, the cryoconite hole will always receive indirect energy and convert that into energy that melts the surface beneath it.

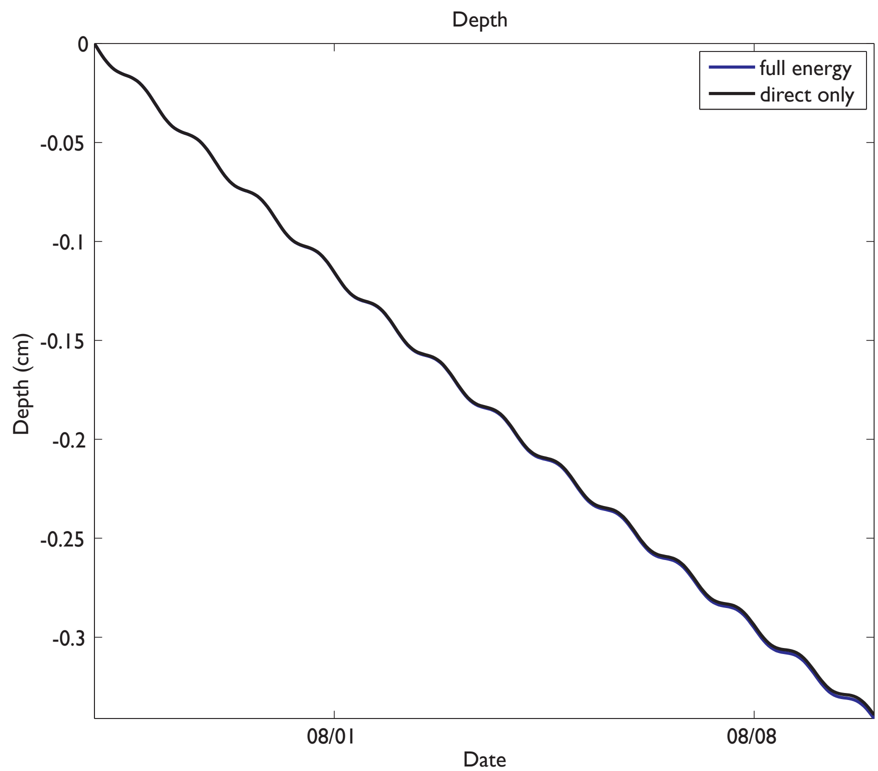

Figure 3.18: *This graph shows how our model measures up against the actual parameters. In this run of the model, the radius was 7cm (the largest cryoconite radius), the albedo of the dirt was 0.15 (the value measured in the field), and the albedo of the ice was 0.45 (the value measured in the field).*

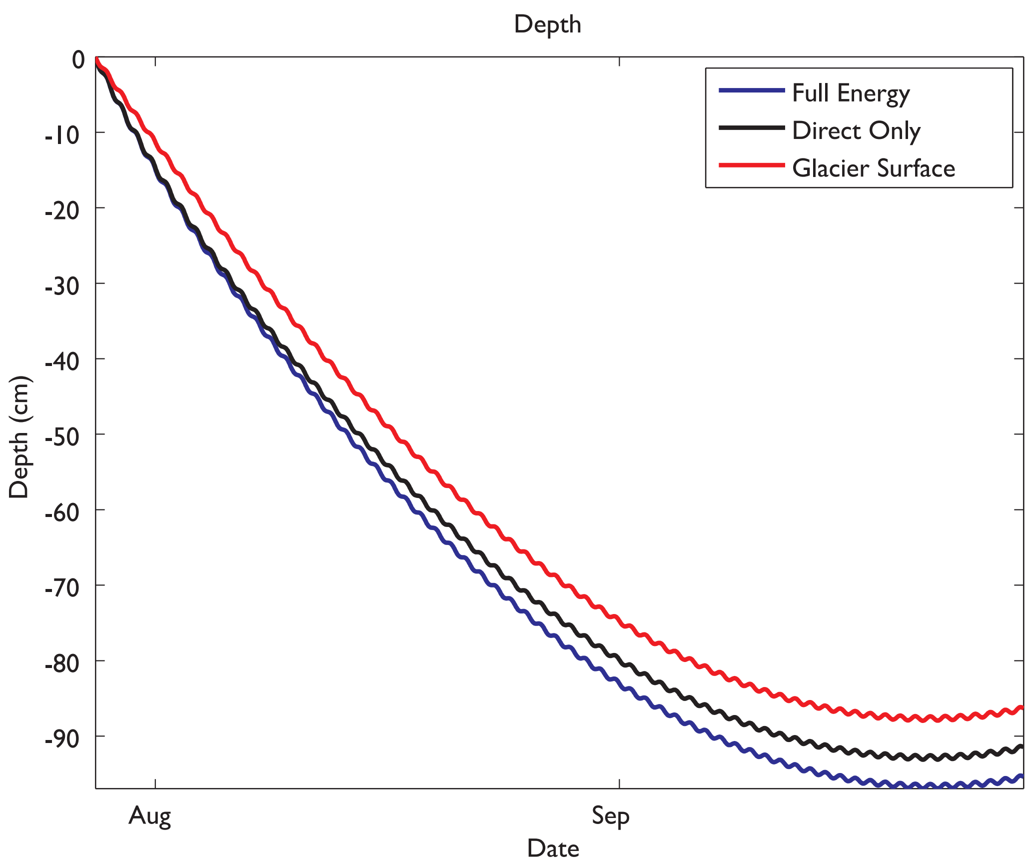

Figure 3.19: *This graph shows the cryoconite depth with the glacier surface melting as well. The red line is the glacier surface height (the purple and black lines remain the same). In this run of the model, the radius was set at 45 cm, the albedo of the dirt was 0.15 (the value measured in the field), and the albedo of the ice was 0.6.*

Chapter 4

Conclusion

The model created was not a very accurate representation of the actual cryoconite holes formed on Linnébreen, as depicted in Figures 3.17 and 3.18. Instead, the model behaved more in line with the cryoconite holes that Fountain looked at in Taylor Valley, Antarctica. If you look at the graphs in Figure 1.3, you can see that the hole with radius of 75 cm (hole 4) melted about 20 cm into the glacier surface at a relatively constant rate over a period of about a month, which is similar to the model projections. The similarities between the model projections and Fountain's data are most likely due the fact that the cryoconite holes in Antarctica are more similar to the parameters of the model. The holes do not change their shape and the radii remain constant throughout time. The biggest difference between the two is the fact that these cryoconite holes were ice-lidded and all of them had water above them, which is probably why the melting rate is a little slower than that predicted in the model.

In order to properly model the cryoconite holes in Svalbard and other arctic glaciers where temperatures are above freezing in the summer, one would need to allow the shape of the cryoconite holes to change throughout time. In other words, to create a model where the sun reflecting off the sides of the hole was radiated in all directions (not just to the cryoconite surface) and the light that was reflected onto the other side of the hole would begin to melt that side of the hole, thus changing the shape of the hole. Another important parameter to add would be the shading effect of the mountains and the frequent clouds. This would add a whole new level to the model and probably begin to slow the melting rate on a day to day basis. And finally, the addition of water to the model would create very interesting effects. If the amount of ice melted was then turned into water and decreased the amount of sunlight hitting the cryoconite surface, it would also decrease the melting speed the more melting occurred.

In addition to creating a new model which takes into account some of the important features of cryoconite holes on Linnébreen, more studies should be done on the evolution of cryoconite holes in the arctic environment. If a new study were done, the sediment should be set out at the beginning of the summer and monitored periodically for as long as possible (ideally for a year). This would enable us to see how the sediment forms into cryoconite holes that naturally occur on the glacier. The sediment set out in this study appeared to take a long time to develop into actual cryoconite holes. In fact, they were still evolving when the two week observation period was over. Each day the measurements showed that the cryoconite radius had increased. If the cryoconite were observed over the entirety of the summer, or for an entire year, hopefully we could get a grasp of how long it takes for a cryoconite hole to form from sediments transported to the glacier so that the radius remained constant.

Further studies should also make sure to spread the different sized cryoconite holes far enough apart to see how each of them evolves without affecting the holes next to them. In my study, the growth of the cryoconite holes eventually reached the hole next to them, occasionally combining sediments. Thus it was difficult to understand how the thickness of the sediment was a parameter in the melting speed. These studies should be done separately in the Antarctic and the Arctic, as comparisons of previous research and the data collected on Linnébreen show that these are two very different environments and need to be understood separately in order to get a full understanding of cryoconite on glacier surfaces.

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