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Temporal Variations in Physical and Chemical Features of Cryoconite Holes on Canada Glacier, McMurdo Dry Valleys, Antarctica

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Temporal variations in physical and chemical features of cryoconite holes on Canada Glacier, McMurdo Dry Valleys, Antarctica

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[1] Cryoconite holes in the McMurdo Dry Valleys are ice-lidded, thus isolating the pools of water from the atmosphere and from potential surface melt. Hourly measurements of ice and water temperature and water electrical conductivity (EC) were recorded to broadly characterize the physical and chemical changes on daily to seasonal timescales. Overall, subsurface ice/water temperatures were typically several degrees warmer than air temperatures, underscoring the importance of subsurface solar heating. At no time was surface melt observed and the holes melted from within. Detailed differences in the timing and magnitude of both temperature and EC variations during melt-out and freezeup existed between holes despite short separation distances (<1 m). We attribute these differences to small-scale changes in the optical characteristics of the ice and perhaps different efficiencies in hydrologic connections between holes. The holes melt-deepened quickly in the first half of the summer before slowing to a rate equal to the rate of surface ablation that kept hole depth constant for the remainder of the season. The relatively constant EC of the hole waters during midsummer indicates that these holes were connected to a subsurface water system that flushed the holes with fresher meltwater. The early and late season ECs are dominated by freeze-thaw effects that concentrate/dilute the solutes. We speculate that high solute concentrations imply high nutrient concentrations in early summer that may help alleviate potential stresses caused by the production of new biomass after the winter freeze.

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1. Introduction

[2] Cryoconite holes are vertical cylindrical melt holes in a glaciers surface, which have a thin layer of sediment at the bottom and are filled with water. The Swedish explorer, A. E. Nordenskjöld, first named these melt holes during his 1870 Greenland expedition: ''cryo'' meaning ice and ''conite'' meaning dust [*Leslie*, 1879]. Cryoconite holes are common to the ablation zone of glaciers worldwide, including the Arctic [*Säwström et al.*, 2002; *Stibal et al.*, 2006; *Von Drygalski*, 1897], the midlatitudes [*Margesin et al.*, 2002; *McIntyre*, 1984; *Wharton and Vinyard*, 1983], and the Antarctic [*Mueller*, 2001; *Wharton et al.*, 1985]. On most glaciers, particularly those in temperate zones, the holes form water-filled pools, with typical horizontal and vertical dimensions of $\sim$10 cm, and maximum dimensions <1 m. In the McMurdo Dry Valleys of Antarctica, cryoconite holes are ice-covered owing to the energy balance conditions on the glacier surface which are unfavorable for surface melt and promote subsurface heating [*Fountain et al.*, 2004].

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[3] In recent years, cryoconite holes have gained attention because they host microbial communities whose activities can alter the chemistry of surface runoff [*Fortner et al.*, 2005; *Hodson et al.*, 2005] and may be an analogue for similar refugia on icy planets [*Nisbet and Sleep*, 2001; *Vincent and Howard-Williams*, 2000] or on Earth during its hypothesized global glaciation (''Snowball Earth'') 600–800 million years ago [*Hoffman et al.*, 1998]. Despite this increased attention, little is known about the temporal evolution of the holes including their physical characteristics, chemistry, or biology. The purpose of this paper is to summarize our direct measurements of temporal variations in hole temperatures and depth, and to broadly infer biogeochemical processes from in situ measurements of electrical conductivity (EC) of the hole waters. We specifically test the equilibrium depth hypothesis of a cryoconite hole [*Wharton et al.*, 1985]. The melt-deepening of a cryoconite hole slows with depth owing to decreased solar heating of the cryoconite with depth. Eventually, hole depth reaches an equilibrium value where the rate of melt-deepening equals surface ablation of the glacier.

2. Site Description and Previous Work

[4] Taylor Valley, one of the McMurdo Dry Valleys, Antarctica, is located on the Ross Sea coast of Southern

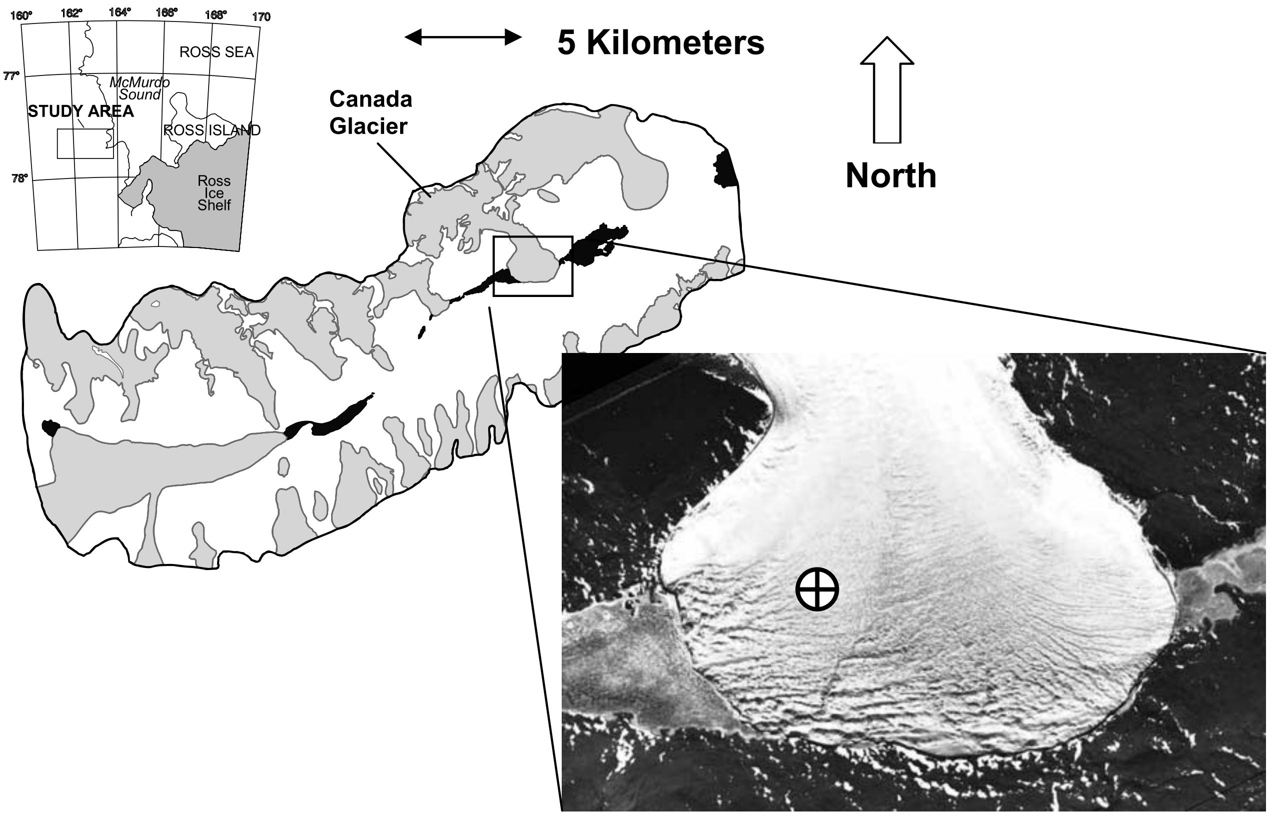

Figure 1. Map of Taylor Valley. The black shapes are the perennially ice-covered lakes, except for the upper right–most shape which is the Ross Sea. The grey shapes are the glaciers. The site location is indicated by the cross mark on the vertical aerial photograph.

Victoria Land, Antarctica, at ~77.5°S and ~163°W (Figure 1). The valley is a polar desert, a barren landscape dominated by a gravely, sandy soil with enclosed, perennially ice-covered, lakes. Polar alpine glaciers descend from the surrounding mountains (1000–2000 m) and the larger glaciers reach the valley bottom where they abruptly terminate in cliffs about 20 m high [*Chinn*, 1985; *Fountain et al.*, 2006, 1998]. Ephemeral streams flow from the glaciers to the lakes for no more than ten weeks during the austral summer [*McKnight et al.*, 1999]. Average annual air temperatures on the valley floors vary from $-15°$ to $-30°C$ with summer temperatures close to freezing [*Doran et al.*, 2002]. Annual precipitation (snow) in the valley bottom averages about 6 cm water equivalent [*Bromley*, 1985; T. H. Nylen, unpublished data, 2006]. However, the snow largely sublimates before making a hydrologic contribution to the streams or lakes and glacier meltwater is the primary source to the streams and lakes [*Chinn*, 1981].

[5] Our study site is located on Canada Glacier, the second largest alpine glacier in Taylor Valley. The glacier starts at about 1600 m elevation and reaches the valley floor, 50 m elevation, where it forms a large lobe almost 4 km across. The lobe is the ice-covered ablation zone, or that low elevation part of the glacier where more glacier mass is lost via ablation (melting, sublimation, calving) than is gained through snow accumulation. The average ablation rate in the ablation zone is ~10 cm a^{-1} and winter (February–October) ablation, via sublimation, is roughly equal to summer (November–January), which is composed of sublimation and melt [*Fountain et al.*, 2006]. Unlike glaciers in more temperate regions, the ablation zones of the dry valley glaciers typically do not accumulate snow in winter [*Fountain et al.*, 1998].

[6] Cryoconite holes in the Dry Valleys were first observed by Scott's expedition [*Taylor*, 1916; *Wright and Priestly*, 1922]. Cryoconite holes found in more temperate regions are subaerial pools of water that freely exchange gases with the atmosphere and exchange water with surface melt, whereas cryoconite holes in the Dry Valleys have ice-lids ~20 cm thick isolating them from the atmosphere [*Fountain et al.*, 2004]. Surface energy balance conditions suppress surface melt due to the advection of cold winds [*Lewis et al.*, 1995]. However, the transmission of solar radiation (radiant energy) into the ice and the relatively slow heat conduction to colder ice at depth or at the surface results in a solid-state greenhouse condition causing internal melt [*Brandt and Warren*, 1993; *Liston et al.*, 1999]. Modeling and observations have shown that the internal melt is probably quite small owing to scattering in the ice, except where sediment is present or the ice is particularly clear (J. Ebnet, unpublished data, 2006). Subsurface sediment absorbs the transmitted solar radiation and expands the range of environmental conditions favorable to internal melt. Formation of cryoconite holes in these conditions results from patches of sediment blown on to the glacier surface, which subsequently melt into the ice followed by

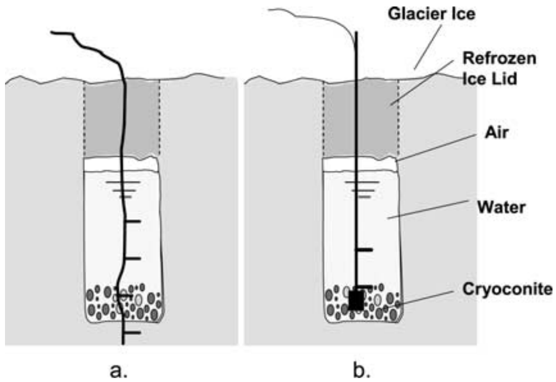

Figure 2. Schematic of a cryoconite hole in the McMurdo Dry Valleys with the two experimental arrangements: (a) electrical conductivity and temperature probes frozen in the ice prior to internal melt out of the hole, Eulerian arrangement; and (b) probes attached to a mast that rides on the sediment, Lagrangian arrangement. The diagram is not to scale, but the hole diameter depicted is about 10 cm. The cryoconite thickness is expanded for visibility in the illustration. The horizontal lines off the vertical wire/mast represent the probes.

surface refreezing. Once in the ice, the solar-heated sediment melts the surrounding ice forming a subsurface pool of water maintained through the solid-state greenhouse [*Fountain et al.*, 2004]. In this state, the cryoconite hole is entombed, freezing and melting beneath the glacier surface for years. However, many cryoconite holes appear to be hydrologically connected to a subsurface system of drainage passages that pipe fresh water though the holes [*Fountain et al.*, 2004]. Other holes appear to be hydraulically isolated, some for a decade, and under these conditions they develop unusual geochemistries [*Tranter et al.*, 2004].

[7] The aeolian transport of sediment from the valley floor also includes biota [*Nkem et al.*, 2006] that inoculate the cryoconite holes. A subset of the biota survives the freeze-thaw cycles and form entombed ecosystems within the holes. A census of microbial organisms in the cryoconite holes of the Dry Valleys includes algae and cyanobacteria [*Mueller*, 2001; *Wharton et al.*, 1985, 1981], as well as rotifers and tardigrades [*Porazinska et al.*, 2004]. In a phylogenetic survey of a single cryoconite hole, [*Christner et al.*, 2003] identified the members of eight bacterial lineages, cyanobacteria, ciliates, green algae, truffles and invertebrates, including nematodes and tardigrades. No study has yet examined the entire foodweb within a cryoconite hole from either a microscopic or a phylogenetic perspective. However, studies of metabolic activity and nutrient analyses suggest active microbial ecosystems exist in the holes [*Foreman et al.*, 2007]. *Tranter et al.* [2004] hypothesize that photosynthesis, presumably by the green algae and cyanobacteria, uses and recycles nutrients scavenged from the inorganic and organic sediments in the hole, as well as from the melted glacier ice. Photosynthesis and hydrolysis of carbonates during the spring thaw can increase the pH to $\sim$10.5, saturate the water with O_2 (160%) and $CaCO_3$, and decrease pCO_2. Thus in these poorly pH-buffered closed systems, there might be negative feedback between photosynthesis and the high pH/low pCO_2, which limits further photosynthesis. Additionally, there may be limitations on new carbon and nutrient sources. The high pH and relatively high concentrations of solute in some of the holes increase the electrical conductivity to relatively high values of $\sim 10^2$ μS cm^{-1} [*Tranter et al.*, 2004]. In general, waters with high conductivity also have high pH.

[8] Although we can broadly outline the physical, chemical, and biological processes that occur within the holes, our specific knowledge of the temporal processes is quite limited. We therefore designed a simple experiment to test some of these notions by tracking temperatures and electrical conductivity in the sediment and in the water above the sediment in several cryoconite holes. The electrical conductivity (EC) is an inexpensive and reliable measurement for long unattended monitoring of water quality. These initial experiments set the stage for future, more sophisticated, efforts. Ultimately we would prefer to track specific biogeochemical processes via changing water chemistries (e.g., O_2, pH), but such probes are not sufficiently robust at present to survive freeze-thaw cycles and long unattended field operation in Antarctica. We believe that time series of EC and temperature variations will provide new insight into the dynamic nature of cryoconite holes over and above those gained from spot sampling of a range of different holes. Hence the goal of this paper is to explore the use of monitoring EC and temperature for determining the chemical and physical dynamics of cryoconite holes.

3. Methods

[9] A site was selected on Canada Glacier for its proximity to our camp. Our first experiment, during the austral season of 2003–2004, monitored six cryoconite holes all located within a 5 m radius. Prior to spring melting, each hole was drilled to the sediment layer using a 1 cm diameter drill bit, probes inserted, and frozen into place using glacier ice melt. Four holes had one pair of temperature and EC probes in the sediment and two holes had two pair of probes, one pair in the sediment and one about 5 cm above the sediment. As the holes melted from within and deepened, the probes stayed in fixed position, providing a fixed frame of reference (Eulerian). Our second experiments during the 2005–2006 season monitored seven cryoconite holes with 2 sets of probes in each hole. We used a Lagrangian approach, where the probes deepened with time as the sediment layer deepened into the ice, but stayed fixed relative to the sediment. The probes were attached to a bicycle spoke that provided a stiff mast for the probes and wire. To prevent the probe from preferentially melting into the ice relative to the sediment, a small pad of sediment was cemented to the end of the spoke. At the bottom of the spoke a thermistor measured sediment temperature. At 5 cm above the sediment, EC and water temperature were measured. During periodic visits we measured spoke depth and assessed whether the spoke was indeed resting on the sediment. Figure 2 shows a schematic of the experimental arrangements of each season.

[10] The temperature probes were Fenwall thermistors (192-502LET-A01) housed in a 5 mm diameter tube filled with silicone adhesive to provide water proofing. The

thermistors were powered using a 279 mV and a 5 K ohm precision reference resistor. The temperature values were calculated from the manufacturers' calibration data and cross compared using an ice bath. The EC probes were manufactured from stainless steel wire also set in the silicone-filled tubes with a separation gap of 4–5 mm and calibrated at 0°C using standard solutions of KCl of known electrical conductivity at 25°C. Therefore the EC values reported are standardized to 25°C. Measured water temperatures are close to 0°C, rarely exceeding 1°C, and the small correction, 0.0187 $°C^{-1}$ [*Hayashi*, 2004], is insignificant. The EC probes were measured using an AC half-bridge and a 50 K ohm precision reference resistor.

[11] We expected our experimental approach to perforate the ice lid entombing the cryoconite hole. On the basis of previous experience we anticipated that solar radiation absorbed by the wire or the spoke will melt the ice surrounding each forming a small passageway that may convey gases between the atmosphere and the hole air space. However, we did not expect the passageway to affect the heating of the sediment, hole waters, or the rate of hole deepening. Temperature differences between the water and surrounding ice are probably small and convective heat transfer is minimal. In addition, the air-filled head space above the cryoconite waters acts as a heat insulator compared to the ice walls surrounding the hole on the sides and bottom.

[12] In addition to probes in the cryoconite holes, during the 2005–2006 season we carefully collected grab samples of the waters from five of the seven holes for EC and geochemical analysis. The purpose was to characterize the bulk waters of the hole rather than the near sediment water. The waters were collected under vacuum using a tube inserted into the hole via the access passage around the instrument cable. The collected waters were drained from the tube into washed 500 mL bottles and rinsed three times with sample water prior to final collection. Samples were filtered through 0.4 μm Whatman nucelopore membranes within 12 hours of collection, and stored at a temperature of <5°C until analysis. The samples were collected intermittently throughout the summer as we visited the site to check the data loggers and made other measurements. Local ice samples where taken to characterize the ice surrounding the cryoconite holes. A SIPRE corer collected 10cm diameter samples of glacier ice to the depth of the cryoconite holes (~40 cm). The ice samples were bagged and melted in the laboratory, filtered and stored as described above. In addition, grab samples of approximately 500 mL were collected from runoff from Canada Glacier prior to contacting the valley floor. The bottles were also triple-rinsed and the samples were filtered and stored as described by *Tranter et al.* [2004]. We report here only the results from the EC measurements.

[13] Finally, a meteorological station was erected to measure wind speed and direction, air temperature and humidity, and solar radiation. A sonic distance ranger measured the distance to surface providing a measure of surface ablation and snow accumulation. These instruments were mounted one meter above the ice surface. Data from the meteorological instruments, sonic ranger, and the probes in the cryoconite holes were recorded using a solid state data logger.

4. Results and Analysis

[14] During the two month experiments the ice surface ablated, the cryoconite holes melted from within, and the sediment floor of the holes deepened with time as had we hoped. Occasional snow during the season blanketed the experimental area. As predicted, the ice surrounding the wire or spoke melted forming a small passageway. At no time did the glacier surface melt.

4.1. The 2003–2004 Season: Eulerian Observations

[15] Depth to hole bottom and therefore to sediment varied between holes from 11 to 30 cm deep. Variations in EC and water temperature in each hole showed similar behavior across all six holes. However, specific behavior and exact timing of warming/cooling and EC variation differed. Over one day from about noon on 3 December to noon on 4 December, the sediment in all holes but one reached 0°C. The order of warming to melting did not correlate with depth to sediment such that deeper sediment warmed first or last. The holes with two temperature probes showed that the sediment depth warmed to the melting point within a few hours prior to the probe 4–6 cm in the ice above. The one hole that did not reach the melting point, Hole 2, was covered with a small patch of snow no more than 2 cm thick. It finally reached melting point on 31 December. With the return of colder air temperatures on Dec 14 the holes started to refreeze roughly in reverse order of melting (last melt to first freeze).

[16] Figure 3 shows the results from Hole 2 with the two temperature probes and one EC probe. The temperature/EC paired probe (18 cm deep) was initially in the sediment. This one was selected over the other hole with paired probes because the latter were moved at some point during the season. As mentioned, this hole melted out last because of the snow patch above it but the record is most complete and undisturbed. The hole began to warm to melting in late December when it lost its snow cover and warmer air temperatures heated the ice. With the onset of melt EC values jumped to nearly 800 $\mu S\ cm^{-1}$ before dropping, after several days, to values closer to 100 $\mu S\ cm^{-1}$. The daily peaks in EC typically occurred in the morning (~1000) local time compared to the peaks in solar radiation (~1600) and air temperature (~1800–2000).

[17] While the temperature exhibited steady variations the EC was quite flashy with a spiky behavior and an overall trend of decreasing EC with time. Once the hole melted, it maintained its temperature until about 13 January, a week after the air temperatures were consistently below freezing, starting about 4 January. Closer to the sediment, temperatures remained above freezing for almost three weeks after cooling air temperatures. Solar heating of the sediment (2.5 hour lag, $r^2 = 0.43$), thermal mass of the sediment, and increasing water density with temperature, up to 4°C, probably interact to keep the near-sediment temperatures relatively warm. By about 13 January, the seasonal cooling of the atmosphere and decreasing solar intensity began to freeze the hole at the top and bottom. EC values were zero,

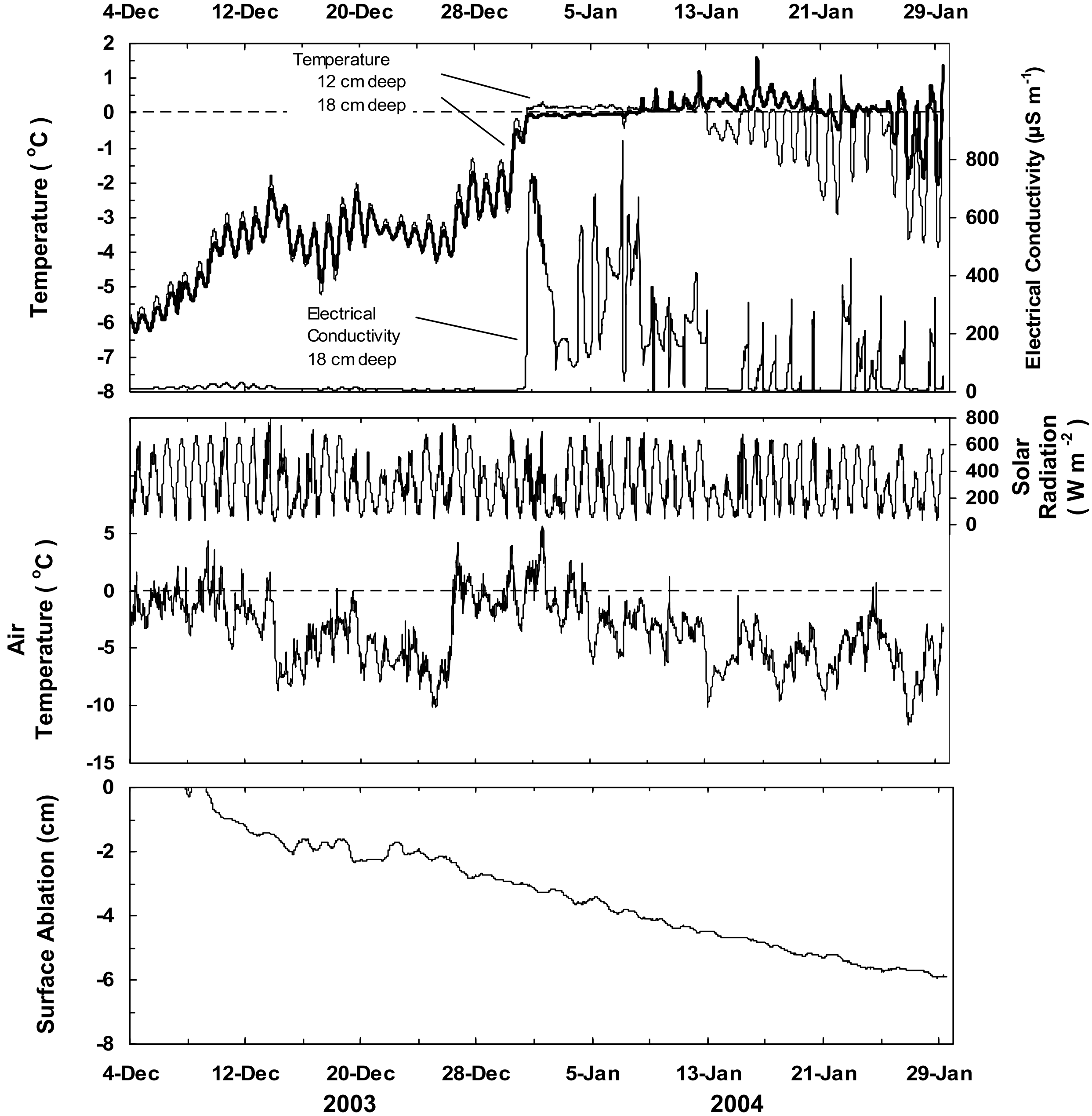

Figure 3. Results from one of the cryoconite holes monitored in 2003–2004. The electrical conductivity and temperature probes were fixed in the ice prior to the onset of melt.

presumably frozen probes, until late afternoon when solar radiation reached its maximum and ice temperatures rose above 0°C and the ice around the probes melted for a few hours before refreezing. The temperature difference between the upper and lower probes increased as the upper probe (12 cm) froze into the thickening ice lid. The actual position of this probe, initially at 12 cm below the surface, by 13 January was about 8 cm below the surface, owing to surface ablation. At the lower probe, near the sediment, the sharp EC excursions and more gentle temperature cycles probably reflect daily melt/refreeze cycles in a small bulb of water around the sensor.

[18] From these results we infer that the detailed differences in temperature and melt onset between holes suggest local variations in optical properties of the surface and subsurface ice because atmospheric properties do not vary substantially across a relatively uniform surface of a few meters. A striking example is the effect of snow on Hole 2. The episodes of abrupt decreases in EC to zero probably reflect melt-freeze cycles around the two short sensing wires of the probe, although the thermistor housed in a relatively large thermal mass of epoxy a mm or so away records temperatures just above freezing. Local thermal effects seem to exert a major influence on the EC measurements and the wire probes may act as ice nucleation sites. That EC is greatest in the morning (~1000) while air temperature and solar radiation are near their minima probably reflects maximum daily freezeup. We hypothesize that first ice melt

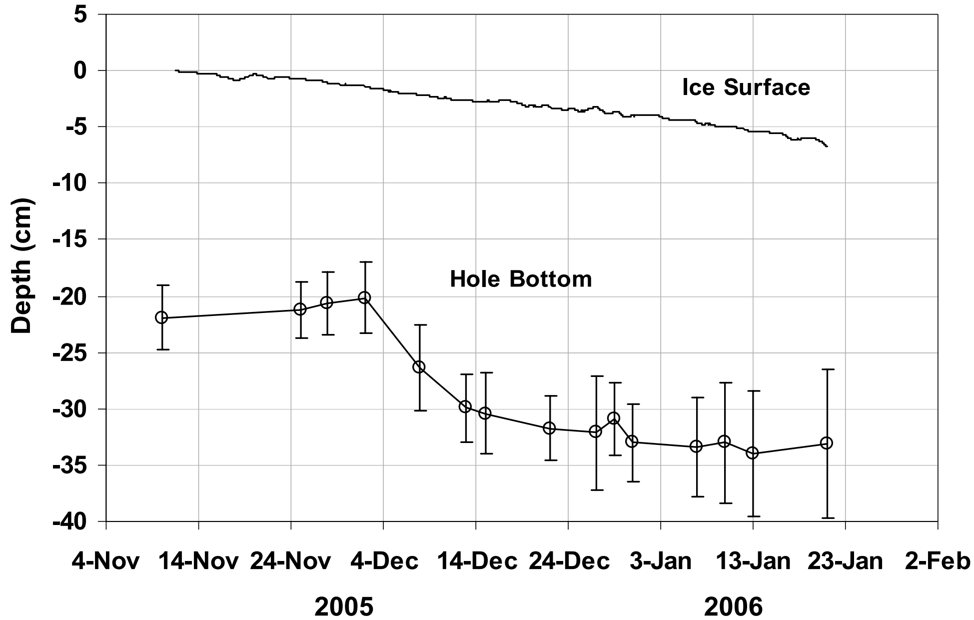

Figure 4. Ice surface height, set to zero at the start of the measurements, and the depth of the bottom of the cryoconite hole with respect to the ice surface. Stated instrument accuracy is 1 cm. Hole bottom is the average of the seven cryoconite holes, and the error bar is the standard deviation of depth. Note that the standard deviation increases with time as different holes deepen differently.

has high conductivity due to solutes scavenged from ice grain boundaries and veins [*Harrison and Raymond*, 1976]. EC may be further enhanced by the hydrolysis of carbonates (the first minerals to be precipitated during freeze) and by photosynthesis of cyanobacteria. The abrupt EC episodes, exhibited in all holes, although different in magnitude and time, probably result from rapid melt-freeze cycles in response to variations in solar radiation. Sustained (days) background levels reflect heterogeneity in geochemical, biological, and physical conditions within and around the holes. Given the potentially large number of biogeochemical interactions, and measurements limited to EC and temperature, more detailed insight is precluded.

[19] We conjecture the following scenario. The abrupt increase in EC and temperature on 30–31 December indicates internal melting of the cryoconite hole. The peak in EC is due to the initial high solute content of the ice near the sediment. The slow decrease in EC after its abrupt initial peak on about 31 December reflects the melt-deepening of the hole that dilutes the solute concentration. Also, the sediment deepens in the glacier relative to the probe such that the probe is higher in the water column and in fresher water. Starting about 2 January, the rising EC background, with sustained sediment (now water) temperatures of 0°C, reflects closed conditions and increased solute content of the water due to photosynthesis. After 9 January the hole became connected to the subsurface water system that flushed the hole with fresher and warmer waters, reducing EC, and slightly increasing water temperatures.

4.2. The 2005–2006 Season: Lagrangian Observations

[20] Depth to hole bottom/sediment varied between holes from 34–41 cm deep. The rate of hole deepening varied somewhat from hole to hole but overall was quite similar. Part of the variation was due to local conditions (e.g., trace snow preferentially collected in depressions over several holes) and part due to the experimental method (e.g., some spokes leaned, skewing measurements of vertical displacement). Results of the water temperature and EC measurements in the seven holes were also broadly similar, although like the Eulerian measurements, details in timing and magnitude differed from hole to hole.

[21] To compare surface ablation to melt-deepening of the holes the ablation was taken from the sonic ranger, which removed variations of individual manual measurements. The manually measured melt-deepening, that is depth to sediment over time, were averaged for all seven holes (Figure 4). Starting about 25 November, the ablation rate of the glacier surface was relatively constant ~ -0.09 cm d^{-1}. Depth from the surface to the hole bottom initially decreased reaching a minimum depth about 2 December. Subsequently, hole depth rapidly increased until about 22 December when the rate slowed to a relatively constant rate of -0.09 cm d^{-1}, matching that of the ablation rate.

[22] Figure 5 shows the results from Hole 5 plotted with air temperature measured at the meteorological station. The obvious diel variation in temperatures was caused by the diel variations in solar radiation intensity. Initially, all temperatures are below freezing and the EC is near zero because the ice entirely encloses the probes. By 24 November, when the ice above the sediment warms to the melting point, the ice at and above the sediment begins to melt and the cryoconite hole begins to reform. During this period the EC varies greatly, similar to the Eulerian experiment, and is probably due to the ice around the probes partially melting and refreezing. In late November air temperatures average about -6°C and the ice 5 cm above the sediment ($\sim$15 cm

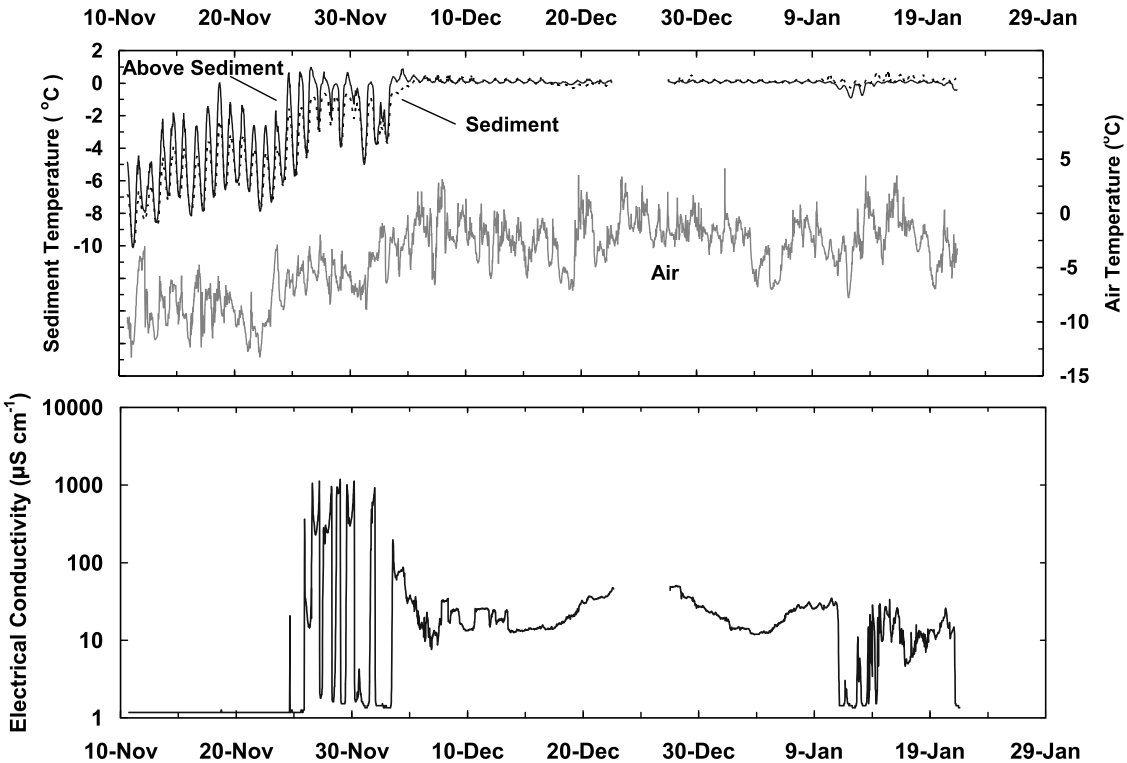

Figure 5. Sediment (dashed line) and water/ice (solid line) temperatures and electrical conductivity in hole 5. The temperature and electrical conductivity were measured 5 cm above the sediment. Air temperatures are measured 1 m above the glacier surface nor more than 5 m away from the hole. The 0°C isotherm is offset to improve legibility of the temperatures.

below the surface) briefly warms to melting each day while the sediment remains below freezing. Both the ice and sediment temperatures were typically several degrees warmer than air temperature. After a cool period of a few days, the sediment and ice 5 cm above both warm to the melting point by the afternoon of 3 December. After melting, temperatures in the hole exhibit minimal variations ($<\pm0.25°C$) for the rest of the experiment through January despite relatively large excursions of air temperature ($\pm3°C$). Similarly, the EC terminated its large fluctuations by the afternoon of 3 December, and also achieved a measure of stability for the rest of the experiment. Unfortunately, we suffered a gap in data recording in late December.

[23] During the period of warm stable temperatures, the sediment temperature was slightly above freezing and the water 5 cm above was slightly below freezing, $\sim-0.5°C$. This temperature is too cold for fresh water and EC values of 20 μS cm^{-1}are insufficient to depress the freezing point significantly. The accuracy of the thermistors is $\pm0.2°C$ and perhaps the cold temperature is due to calibration error. Alternatively, if ice did form around the probe the minimal temperature variation suggests the ice-covered probe is immersed in water such that temperature variations are minimal. The grab samples of water from the holes were more intermittent than desired. Access into the holes was limited and we did not want to break open a new passage or enlarge an existing one: therefore we only collected samples when access allowed. Overall, the EC of the bulk waters from the holes and the glacial runoff showed a decrease in time (Figure 6). Four of the five holes exhibited an EC higher than the runoff and the EC of glacier ice is much lower than the waters as expected.

[24] From these results we infer that the initial decreasing (shallower) hole depth was common to the measured holes and may be due to melt-freeze cycles in late November. The melt around the pad probably refreezes under the pad slowly elevating the spoke with each cycle until the hole warms entirely on 4 December ending the melt-freeze events. As expected [*Fountain et al.*, 2004], the rate of hole deepening was faster earlier in the season than later. As we show below, hole deepening reaches an equilibrium depth by the end of the melt season and the sediment freezes in place as the hole freezes closed. Over winter, ablation of the glacier surface reduces the depth to the sediment and by spring it is less than the equilibrium depth. Consequently, solar heating of the sediment and subsequent melt exceeds the rate of ablation at the glacier surface and the hole deepens rapidly. The winter ablation at this site was 9.9 cm from late January to early November 2005. The initial rapid phase of deepening accounted for 9.5 cm (not including the decreased depth) by 22 December. In late December, the rate of melt deepening had slowed and matched the rate of surface ablation (~-0.09 cm d^{-1}); hole depth reached its nominal equilibrium value of 28.6 cm. This result supports *Wharton et al.*'s [1985] hypothesis regarding the equilibrium depth of cryoconite holes and our hypotheses of seasonal hole evolution.

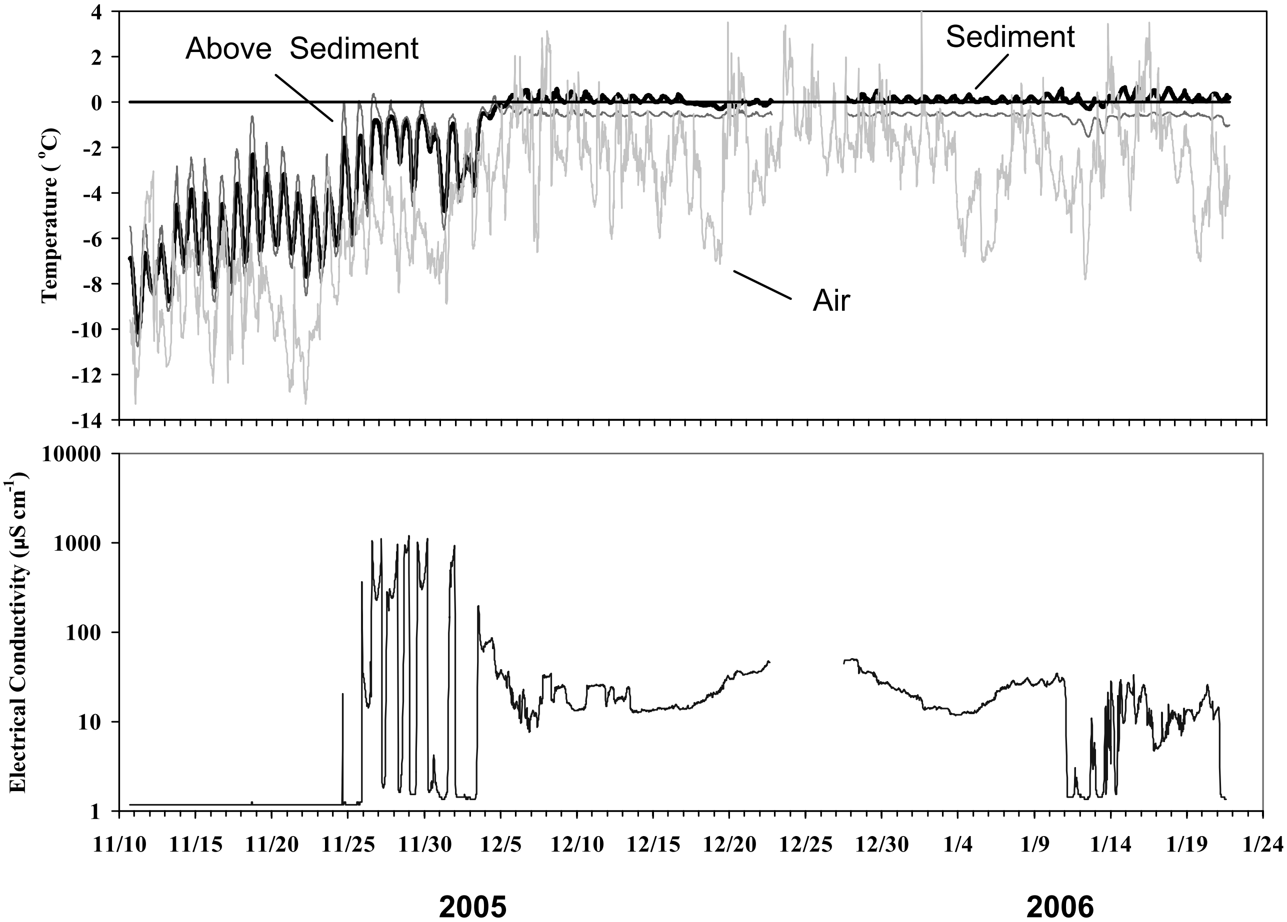

Figure 6. Results of grab samples during the 2005–2006 season of electrical conductivity from the cryoconite holes, the bulk ice, and the runoff from the glacier.

[25] The behavior of the temperature and EC measurements reflects those of the Eulerian experiment. Diel variations of temperature become damped when temperatures reach melting. At this point the EC fluctuates widely probably reflecting cycles of melt-refreezing. Like before, the extreme values of EC ($\sim$1000 μS cm^{-1}) probably reflect the elevated concentration of solutes in the first melt, possibly augmented by hydrolysis of carbonates and photosynthetic activity. Clearly, the general melt out on 3 December damped the EC fluctuations and over the next two days EC values dropped to about 20 μS cm^{-1}. The drop in EC coincides with the hole deepening (see Figure 4), and is probably a result of dilution as the hole reforms. The EC magnitude of 20 μS cm^{-1} could be a result of dissolution of solutes from the sediment that is slowly flushed with water. Typical values of melted glacier ice in the Dry Valleys are only a few μS cm^{-1} (Figure 6) [*Lyons et al.*, 2003] and higher values indicate other sources of solute must be available to the hole. Dissolution experiments with fresh cryoconite sediment in an isolated chamber exhibit EC values of closer to 100 μS cm^{-1} or more [*Tranter et al.*, 2004], but the ability of sediment to supply solutes decreases over time as reactive minerals are exhausted. The relatively low values, which did not exceed 50 μS cm^{-1} after 6 December, suggest that this cryoconite hole was probably hydraulically connected to other holes and was flushed with fresh meltwaters. We speculate that higher values of EC were not observed in this hole because of the construction of the pad at the base of the spoke. A glue was used that slowly disintegrated in water, poisoning the waters and killing the cyanobacteria, diagnosed by high concentrations of DOC and undepleted trace nutrients when compared to other 'live' cryoconite holes sampled in the vicinity (E. Bagshaw, unpublished data, 2006).

[26] The EC of the runoff and bulk cryoconite waters decreased over time (Figure 6). We attribute the decreasing EC of the holes to dilution and flushing of solutes from the glacier surface and cryoconite holes, and to the decrease in the residence time of water in the supraglacial drainage system, which reduces the time available for sediment-water interactions during the transit of waters to the glacier terminus [*Fortner et al.*, 2005]. The variation of EC among the cryoconite holes is quite variable and may reflect individual melt-out histories and degree of dilution, and the efficiency of the hydraulic connection between holes. Efficiently connected holes have lower EC and those poorly connected have high EC values. Indeed, Hole 4 is the most dilute and was visibly connected to a crack-like feature with water flowing through the hole. That the bulk runoff from the glacier had an EC lower than the holes measured, except for Hole 4 which had water flow observed through the hole, and higher than the bulk ice EC indicates that the runoff is a

mixture of cryoconite waters and bulk ice melt. Using a simple mixing model [*Collins*, 1979] the relative fractions of contributing sources (cryoconite melt versus bulk ice melt) to runoff can be calculated. Considering the time period when the EC values begin to stabilize, 28–30 December, the average value of the cryoconite waters was 28 μS cm^{-1}, 9 μS cm^{-1} for bulk ice, and 12 μS cm^{-1} for runoff (Figure 6), Mass balance suggests that 15% of the runoff is derived from the cryoconite holes. This compares favorably with 13% estimated by *Fountain et al.* [2004] using an entirely different method and for a different year.

5. Discussion

[27] In early summer, prior to the melt out of the cryoconite holes, internal heating is evident in both experiments. That the interior ice temperature is warmer than the air temperature, commonly by 5°C or more, clearly supports the hypothesis of subsurface heating in the Antarctic environment [e.g., *Liston et al.*, 1999]. The magnitude of subsurface heating varies somewhat between holes and points to small-scale variations in the optical properties of the surface and subsurface ice. It cannot be an effect of the local atmosphere and there is no strong correlation with depth to sediment over the small ranges measured. Furthermore, we see no reason for large variation in the thermal conductivity of the ice. Variability in transmitted solar radiation may affect the EC via differences in melt rate resulting in differences in dilution. Moreover, differences in solar heating may affect solute dissolution and photosynthesis by altering the timing, magnitude and duration of water within the holes [*Huner et al.*, 1998; *Tranter*, 2003]. Another important process affecting EC is the efficiency of subsurface hydrologic connections that recharge the holes with dilute waters and flushes solute downstream.

[28] The initial fast rate of hole deepening and subsequent slowing supports the conceptual model of seasonal hole evolution outlined by *Fountain et al.* [2004]. That the rate of deepening slows to match that of surface ablation supports the *Wharton et al.* [1985] model of an equilibrium hole depth. The experimental verification of these hypotheses provides confidence in our growing understanding of the energy balance of the holes.

[29] Our indirect measurements of hole chemistry using EC yields generalized but useful new information about the physical and chemical environment within which biogeochemical processes occur. High EC values during the initial melting reflect the initial melt of brine ice created during freezeup, the dissolution of carbonates, which are the first minerals precipitated during the freeze, and probably photosynthesis in closed voids where the water content is low. The latter is consistent with laboratory experiments which show that photosynthesis occurs very quickly following thaw [*Stibal and Tranter*, 2007]. Dissolution of the other inorganic fractions of the cryoconite debris probably does not contribute much solute at this stage owing to the slower dissolution kinetics of common silicates. They are likely to be more important on timescales of weeks to months. The near diel pattern of EC in the early stages of hole development could carry an imprint of photosynthesis, but is most likely a consequence of melt-freeze cycles, which are a consequence of the poor thermal buffering in the holes when there is relatively little water present. These first relatively concentrated waters, which can be 2 orders of magnitude more concentrated than waters in the fully thawed holes, may be advantageous to photosynthetic organisms because nutrient concentrations will be higher when photosynthesis resumes after the winter freeze, reducing a potential stress on the production of new biomass.

[30] On a daily cycle, peak EC does not occur during maximum solar intensity, pointing to dilution when water production is high, but occurs either early or late in the day depending on the hole, when there is a greater likelihood of net freezing. Local surface conditions, such as distribution of snow patches, may dictate when the hole receives sufficient radiation. The Sun at this latitude is always above the horizon in summer so transmission of radiation through the ice depends partly on surface conditions.

[31] Over the season, EC values in the holes decrease with time, supporting the idea that the holes are not hydrologically isolated and mix with other subsurface waters. The degree of mixing is unclear but a rough calculation indicates that roughly 15% of the runoff from the glacier is derived from cryoconite water. The most dilute hole, based on the grab samples, is also the hole with water observed flowing through it. The bulk behavior of the system, as indicated by the decreasing EC values of the runoff, is suggestive of a system draining its solutes.

[32] These complex patterns of water temperature and EC suggest complex interactions between geochemical, physical, and biological processes in each hole that combine to form quite different biogeochemical characteristics and rates of evolution. It appears that on a broad scale most holes act similarly, more or less melting out and freezing up within hours to a day apart, with similar EC behavior. However, specific details of timing, solute concentrations, and perhaps biological activity are very different owing to optical characteristics of the ice and the efficiency of hydrological connections between holes.

[33] We outline a generalized summer evolution of a cryoconite hole found on the glaciers of the McMurdo Dry Valleys on the basis of the observations above (Figure 7). Ice temperatures in early November are still well below freezing and the sediment is frozen in place. Solar radiation warms the sediment sufficiently such that both the sediment and surrounding ice melts. The sediment melt-deepens into the ice, creating a thin layer of water above the sediment. The sediment is subject to daily freeze thaw cycles until there is sufficient thermal inertia in the sediment and water to prevent freezing during periods of low diurnal radiation. Photosynthesis of the green algae and cyanobacteria on the sediment occurs almost as soon as liquid water is present [*Stibal and Tranter*, 2007], creating oxygen and salts, including carbonates, precipitated during the previous freeze. The salts rapidly dissolve and increase the solute content of the waters [*Tranter et al.*, 2004]. The oxygen and air bubbles melted from the ice form a headspace at the top of the hole. This process continues through early December and the hole melt-deepens rapidly. The solute content of the waters continues to increase because of solute scavenging from the glacier ice melt and the dissolution of cryoconite [*Bagshaw et al.*, 2007]. Hydraulic passageways are established by the subsurface water system by mid-December. How they form is currently unknown,

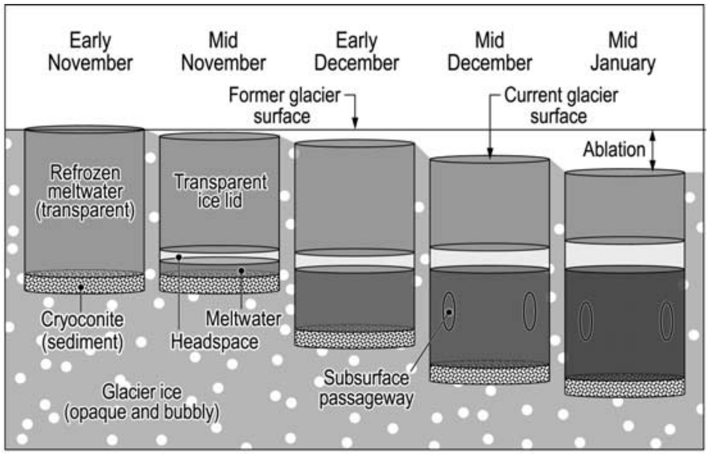

Figure 7. Hypothetical evolution of a cryoconite hole in a Dry Valley glacier. Note that the glacier surface ablates with time and the hole melts from within. The color of the meltwater darkens with time, indicating less solutes. The head space is the accumulated gases from photosynthesis and from bubble melted out from the ice. Equilibrium is established between surface ablation rate and melt-deepening of the hole bottom by mid-December such that the cryoconite hole itself does not change height between the last two time periods.

although we have observed pipe-like connections that may result from crack traces of former crevasses [*Fountain et al.*, 2004]. The holes are flushed with relatively fresh meltwater lowering the solute content. The sediment has reached its equilibrium depth such that its rate of melt-deepening has slowed to the ablation rate of the glacier surface and for the remainder of the summer the sediment depth is constant. Air temperatures cool by mid-January as the Sun is lower on the horizon. Consequently, the ice and sediment cool and the cryoconite holes begin to freeze. They are frozen solid by mid-February. The surface continues to ablate through the winter, reducing the depth to frozen sediment until the following November, when the cycle repeats itself.

6. Conclusions

[34] Significant solar heating of subsurface sediment occurs in glacial ice of the McMurdo Dry Valleys. Spatial variations in the optical properties of the surface and near-surface ice seem to play an important role in the rate and timing of subsurface heating and eventual internal melt-out of the cryoconite holes. Surface snow, even thin ($\sim$cm) covers, drastically reduces subsurface heating by increasing surface albedo. Holes melt-deepen rapidly early in the summer season and slow to an equilibrium depth late in the season. Initial rapid melt-deepening is caused by winter sublimation of the glacier surface that reduces the depth to sediment from the equilibrium depth at the end of the previous summer. Equilibrium depth is established when the deepening rate matches surface ablation, supporting previous theory.

[35] Electrical conductivity of the hole waters provides a useful, but coarse, indicator of hole chemistry. During initial melt-out of the holes, the EC can be 2 orders of magnitude higher than later in the season and may facilitate photosynthesis of the resident cyanobacteria by supplying the required nutrients in high concentrations. That the holes exhibited lower EC values with time indicated hydraulic connections with fresher meltwaters. The connections must be subsurface because no surface melt was observed during the period of observations. These connected cryoconite holes supply about 15% of the runoff draining from the glacier, supporting estimates of prior work.

[36] Variability in subsurface solar heating, controlled by optical properties of the ice, and the efficiency of hydraulic connections between holes are important physical processes that affect chemistry of the hole waters. Photosynthesis by the cyanobacteria and solute dissolution from the sediment are the important biogeochemical processes. Together, these processes control the variation in water chemistry between cryoconite holes and perhaps significantly influence the biota as well.

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