Role of a Supraglacial Snowpack in Mediating the Delivery of Meltwater to the Glacier System: Implications for Glacier Dynamics?

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ABSTRACT:

The flow of water through subglacial drainage systems plays a critical role in controlling glacier dynamics, and hydrological conditions in the supraglacial snowpack will act to mediate the delivery of melt water from the snowpack surface to the rest of the glacier system. However, the hydrological behavior of the supraglacial snowpack has not yet been investigated in conjunction with season-long information on subglacial conditions and ice dynamics.

Data collected during the 2004 melt season at Haut Glacier d'Arolla, Valais, Switzerland, provides information on the hydrological behavior of the supraglacial snowpack and its evolution over the course of the melt season. Observations of the movement of dye-stained water show the complexity of flow patterns and the influence of ice layers in delaying percolation through the snowpack, while fluorometric techniques yield average flow rates for percolation through the snowpack of between 0.13 and 0.49 mhr^{-1}. The changing form of dye return curves and increasing percolation rates suggest an increase over the course of the melt season in the efficiency with which the snowpack transmits meltwater.

Although abnormally low melt conditions throughout summer 2004 prevented the occurrence of a spring glacier speed-up event comparable to those observed in previous years, the observed hydrological behavior of the supraglacial snowpack suggests that it may play an important role in controlling discharge into the subglacial system, and potentially glacier dynamics. This effect can only be fully understood by considering the hydrological behavior of a heterogeneous snowpack and its evolution throughout the melt season.

Keywords: snow hydrology, percolation, spring dynamic event, ice layers, Haut Glacier d'Arolla

INTRODUCTION

Hydrological conditions in the subglacial drainage system play a critical role in determining rates of glacier motion by basal sliding (Iken and Bindschadler, 1986; Willis, 1995; Harbor et al., 1997), and considerable research has advanced our understanding of subglacial drainage configurations, their associated hydraulics (Kamb, 1987; Humphrey, 1987; Hooke et al., 1990; Hubbard et al., 1995) and their evolution through time (Hock and Hooke, 1993; Nienow et al.,

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1998). In recent years it has been increasingly recognized that seasonal changes in the structure of subglacial drainage systems may in fact be driven by processes taking place in the supraglacial drainage systems that feed them (Fountain, 1996; Nienow, 1997; Fountain and Walder, 1998; Sharp et al., 1998). In particular, the presence of a supraglacial snowpack and its hydrological behavior will mediate the delivery of melt water to the rest of the glacier system. Studies of snow hydrology in non-glacial environments have shown that flow through snow acts to dampen and delay the passage of the diurnal melt water wave (Colbeck, 1972; Colbeck and Davidson, 1972; Jordan, 1983), and analyses of seasonal changes in the shape and timing of diurnal runoff hydrographs from glaciers show that such effects also apply in the glacial environment (Elliston, 1973; Fountain, 1992, 1996; Hannah et al., 1999). It has been suggested that the varying thickness of the snowpack may play a critical role in controlling the timing of the 'spring event' (Röthlisberger and Lang, 1987, p.262; Nienow, 1997) observed at several glaciers, a period of enhanced glacier flow thought to be caused by increased discharge into a hydraulically inefficient subglacial drainage system. Despite these observations, the hydrological behavior of the supraglacial snowpack and its relationship to ice dynamics remains poorly understood.

A field program was therefore undertaken to explicitly investigate the hydrological behavior of the supraglacial snowpack an alpine glacier and its evolution during one summer melt season. Observations of dye movement in excavated snowpits qualitatively reveal patterns of flow, while quantitative fluorometric techniques provide information on rates of water movement in the snowpack.

This paper presents results from both qualitative and quantitative investigations in the snowpack, to determine the nature of and factors controlling seasonal variations in water flow. Photographic records of dye movement are used to identify flow patterns within the snowpack throughout the melt season. Dye return curves and percolation velocities derived from dye tracing are analyzed to determine if and how the snowpack evolves hydraulically over the melt-season. Finally, possible links between the hydrological behavior of the snowpack and the occurrence of the glacier 'spring event' are discussed.

FIELD SITE AND DATA COLLECTION

Field data was collected during the summer melt season of 2004 (early May until late July) at Haut Glacier d'Arolla, a 4-km-long temperate valley glacier in canton Valais, Switzerland. The glacier ranges in altitude from around 2600m to over 3500m a.s.l. with an area of approximately 6.3km^2 (Willis et al., 2002). Since the early 1990s the Haut Glacier d'Arolla has been the subject of a series of studies that have yielded a detailed understanding of the subglacial hydrological system, its variation both in time and space, and its links to spatial and temporal patterns of glacier surface motion (Hubbard et al., 1995; Nienow et al., 1998; Mair et al., 2001). This existing knowledge of glacier hydrology and dynamics makes Haut Glacier d'Arolla an ideal location at which to attempt to incorporate the role of supraglacial snow hydrology into our understanding of the glacier hydrology-dynamics relationship.

Field investigation of water movement in snow poses significant challenges due to the heterogeneous nature of natural snowpacks (Marsh, 1999; Harper and Bradford, 2003; Kronholm et al, 2004) and their continuous evolution in response to a number of factors. Correspondingly, field investigations of snow hydrology are crucial in order to understand the complexities of the natural snow system and better suggest ways in which such complexity may be represented in modeling work. Previous studies of snow hydrology have used a variety of techniques to assess water movement through the snowpack, including lysimeters to measure water discharge at depth (Colbeck and Anderson, 1982; Jordan, 1983; Marsh and Woo, 1985; Harrington and Bales, 1998), thermistors measuring the changes in heat flux caused by percolating meltwater (Conway and Raymond, 1993; Sturm and Holmgren, 1993; Conway and Benedict, 1994), capacitance meter measurements of snowpack liquid water content (Gerdel, 1954; Singh et al., 1999), monitoring of the water level at the snow-ice interface (Schneider, 2001), pumping and slug tests to determine hydraulic conductivity (Fountain, 1989; Schneider, 1999), and observations of dye movement through snow (Gerdel, 1954; Schneebeli, 1995; Albert et al., 1999; Kattelmann and Dozier, 1999).

In this study dye tracer tests are used as the primary method of obtaining information about water flow through the snowpack. Dye tracing has been extensively used in subglacial hydrology and in other hydrological systems (Käss, 1998) and has a long history of use in snow, but in the past has generally provided only a visual indication of patterns of water movement. In this study the use of a down-borehole fluorometer installed at the snow-ice interface also enabled accurate detection of dye concentrations and the recovery of quantitative information about rates of dye movement through the snowpack.

Methodology

For qualitative dye injections, the dye rhodamine WT was spread in solution on the undisturbed snowpack surface using a spray dispenser and allowed to flow naturally through the snowpack for a known time before excavations were made into the snowpack in the vicinity of the 'injection' area enabling examination of meltwater flow patterns. Excavations of two types were made: into the upglacier wall of a snowpit, to examine percolation through the snow section across-slope, and into the side wall of a snowpit, to examine the distribution of dye movement in the downslope direction over sloping ice layers within the snowpack. Photographs of flow patterns were taken with a 4 megapixel digital camera immediately after excavation. In all injections the minimum possible amount of water (typically 70ml over 1m^2) was used to spread dye, in order that the added water would not significantly affect the natural development of the snowpack.

The typical experimental set-up for quantitative dye injections on the snowpack surface is shown in Figure 1. Fluorescent dye (either rhodamine WT or fluorescein) was spread in solution on the snow surface and allowed to flow naturally through the snowpack. The fluorometer was installed at the snow-ice interface a known distance downglacier (typically 3 to 4 meters) to detect dye arriving in the saturated layer at the base of the snowpack. The return curves obtained are analyzed to obtain information about rates of dye movement through the snowpack.

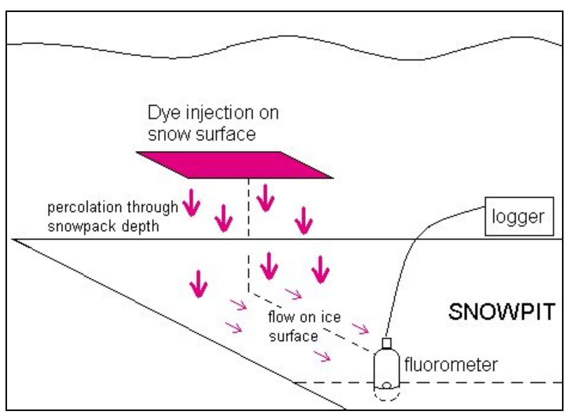

Figure 1. Typical experimental set-up for dye injections on the snowpack surface.

Experiments were also undertaken with 2–3ml of dye in solution injected through a borehole in the snowpack directly into the basal saturated layer. Dye traveled through the basal saturated layer above the largely impermeable ice surface before detection at the fluorometer, with results giving information about flow through this part of the snowpack hydrological system.

Dye injections were carried out at a study station 1km upglacier from the snout. The data obtained provides a detailed picture of snowpack evolution at two adjacent snow pits at 2750m elevation. Two injection pits were used in rotation such that dye could be naturally flushed out of the system at one pit before the next experiment there was carried out. Repeat injections at a pit were carried out on the same area of the snowpack surface. It is hoped that this will help to reduce variation in return times caused by differing flow at the snowpack base and therefore render curves obtained from the same pit comparable across the melt season. Quantitative surface dye injections at this location in summer 2004 yielded a total of 13 return curves from which percolation rates can be obtained. Experiments were carried out throughout the melt season, with successful returns obtained between 14th June and 10th July. Earlier experiments were unsuccessful as ice layers within the snowpack prevented dye from reaching the base of the snowpack within the 3 meters between the injection area and the fluorometer.

Other data provide additional information relevant to the hydrological evolution of the snowpack. A Campbell Scientific SR50 ultrasonic depth gauge was mounted close to the snow pits and provides a continuous record of snowpack depth changes. A radiation-shielded Campbell Scientific 107 thermistor measured air temperature at 2 meters above the snow surface at a nearby automatic weather station. Changes in snowpack properties were monitored throughout the study period by taking stratigraphic and density profiles every 3–4 days.

Snow conditions during the 2004 melt season

The onset of melt in 2004 was delayed by cold weather and regular snowfall throughout May, and continued poor weather resulted in the survival of a snowpack of significant depth until mid July (Figure 2). Patches of bare ice first appeared at the end of June near the western margin of the glacier around 800m from the snout, with the snowline retreating from the tongue of the glacier to the snow pit location over the next 4 weeks. Due to poor weather conditions melt volumes were generally low, with peak daily melt flux only rarely reaching 0.0001cms^{-1} (3.6 mm w.e. h^{-1}). Between 14th June and 10th July the ultrasonic depth gauge indicated surface lowering from around 2m to 0.75m at the snow study station, and dye returns from this period therefore present a picture of the snowpack's changing hydrological behavior as it melts and ablates.

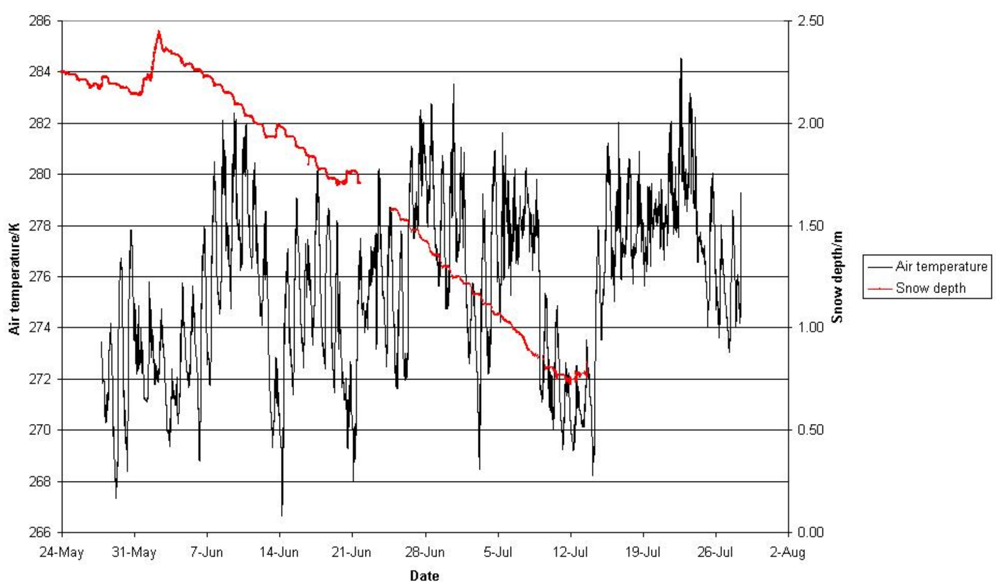

Figure 2: Air temperature (as an indicator of melt volume) and snow depth at the snow pits during the 2004 melt season.

RESULTS

Qualitative dye injections

Qualitative dye injections and snowpack excavations reveal dye movement through the snowpack at different stages of the melt season. A selection of representative photos are shown in Figures 3–7 below and discussed later.

Figure 3: Ice layers causing retention of percolating meltwater and lateral variability of flow.

Figure 4: Retention of water by a near-surface ice layer, previously permeable to water flow, due to cold conditions.

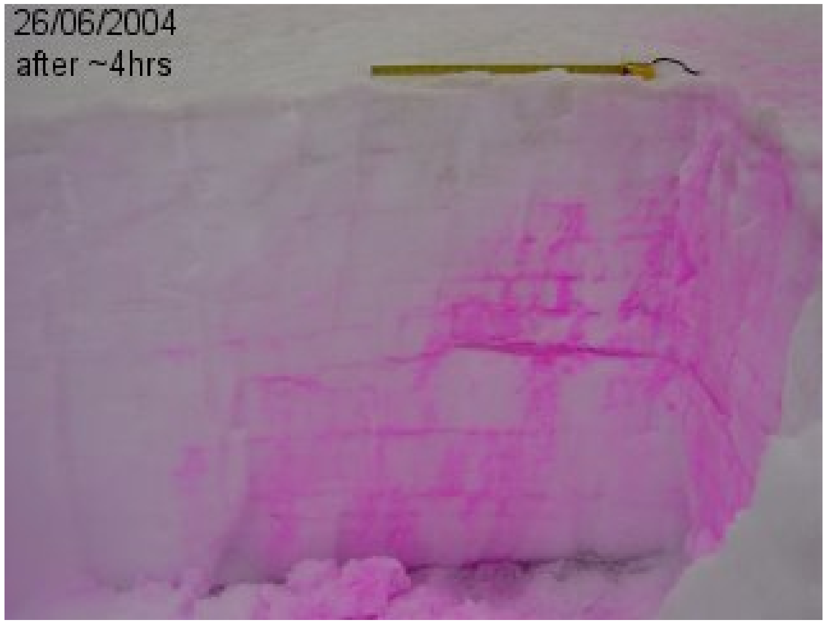

Figure 5: Sideways excavation into snowpack showing significant forward flow of percolating water along ice layers.

Figure 6: Heterogeneous flow around ice lenses on 27/06/2004.

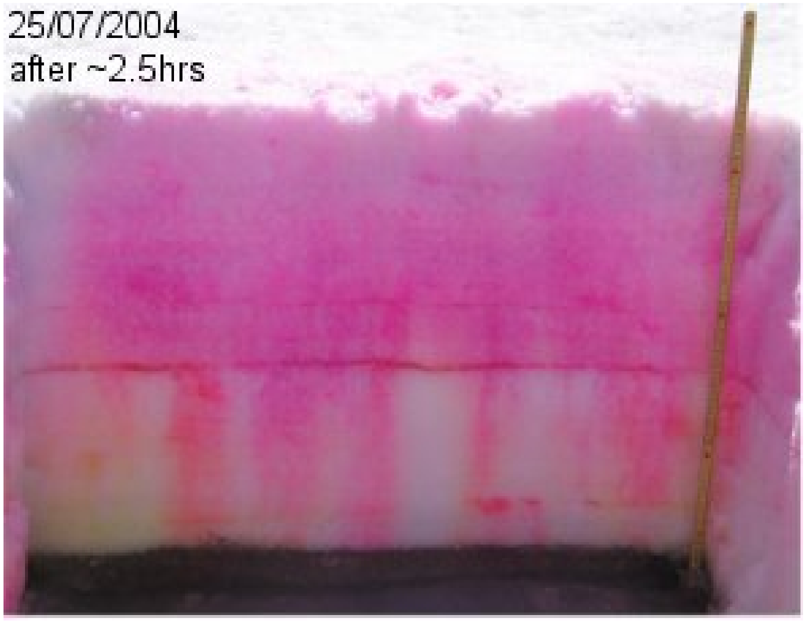

Figure 7: Dye percolation late in the melt season, indicating more homogeneous percolation yet continuing role of ice layers at depth.

Quantitative dye injections

Figures 8 and 9 show the return curves obtained from surface injections at Pits A and B respectively.

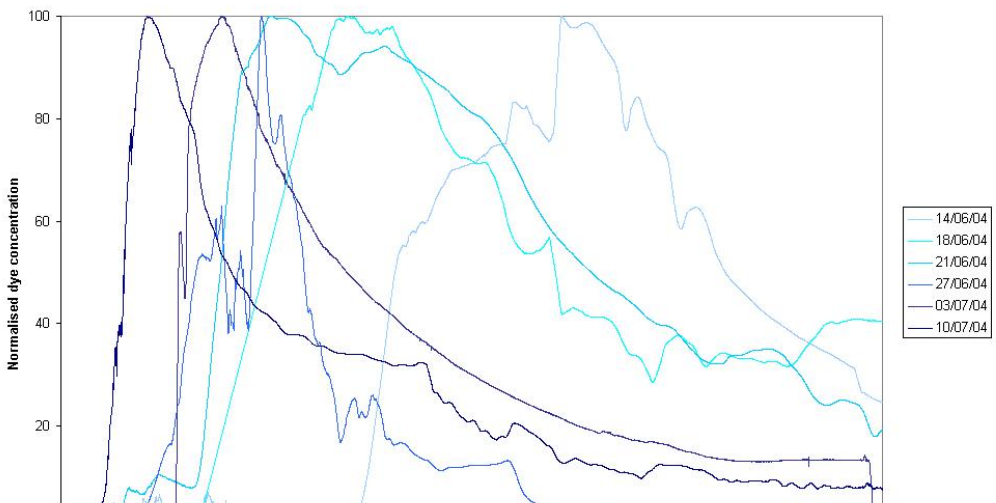

Figure 8: Return curves from Pit A.

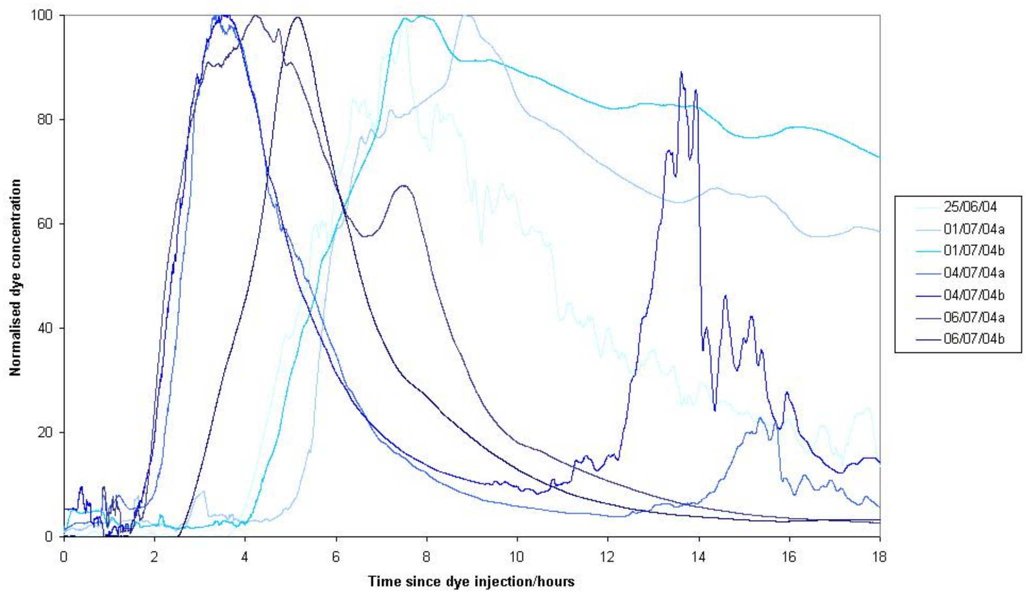

Figure 9: Return curves from Pit B.

Velocities of dye percolation

The time to peak dye concentration for each return curve was used to calculate a modal flow velocity for dye movement. As return curves observed at the fluorometer are the net result of percolation through the snowpack plus flow along the ice surface, percolation velocities were derived by subtracting travel times for flow through the basal saturated layer, assumed to take place at a rate of between 3 and 25 mhr^{-1} in accordance with the results of dye injections at the snow-ice interface. The resulting percolation velocities are presented in Tables 1 and 2 along with information about the date, time, snow depth and flux conditions for each injection and the transit time to peak concentration read from each return curve.

Table 1: Information about injections carried out at Pit A.

Date	Location	Time of injection	Transit time to peak dye concentration/hrs	Snow depth/m	Water flux/ cm^2	Modal velocity/mhr^{-1}
14/06/2004	Pit A	12:13	10.90	1.75	1.20x10^{-4}	0.17
18/06/2004	Pit A	12:54	6.01	1.54	2.15x10^{-4}	0.29
21/06/2004	Pit A	14:26	4.60	1.53	2.37x10^{-4}	0.39
27/06/2004	Pit A	11:30	4.41	1.23	1.66x10^{-4}	0.33
27/06/2004	Pit A	14:02	4.40	1.23	1.34x10^{-4}	0.33
03/07/2004	Pit A	15:48	3.51	0.92	1.71x10^{-4}	0.33
10/07/2004	Pit A	15:58	1.95	0.58	1.12x10^{-4}	0.49

Table 2: Information about injections carried out at Pit B.

Date	Location	Time of injection	Transit time to peak dye concentration/hrs	Snow depth/m	Water flux/ cm^2	Modal velocity/mhr^{-1}
25/06/2004	Pit B	11:27	7.52	1.35	$1.62x10^{-4}$	0.20
01/07/2004	Pit B	12:03	8.82	1.03	$1.06x10^{-4}$	0.13
01/07/2004	Pit B	13:34	7.90	1.03	$0.76x10^{-4}$	0.14
04/07/2004	Pit B	12:18	3.30	0.89	$1.70x10^{-4}$	0.34
04/07/2004	Pit B	14:03	3.53	0.89	$1.66x10^{-4}$	0.31
06/07/2004	Pit B	10:31	4.19	0.79	$0.82x10^{-4}$	0.22
06/07/2004	Pit B	13:03	5.16	0.79	$1.19x10^{-4}$	0.18

INTERPRETATION

Patterns of water movement in a supraglacial snowpack

Observations of dye movement show water flow within the snowpack to be highly heterogeneous. Simple snow hydrology models have represented snow as a homogeneous, porous medium in which water percolates as a uniform wave (Colbeck, 1972). Although such models have been shown to provide good results in a laboratory setting, field studies have demonstrated the much more complex way in which water frequently percolates through natural snowpacks (Gerdel, 1954; Marsh and Woo, 1985McGurk and Marsh, 1995; Schneebeli, 1995; Kattelman and Dozier, 1999; Waldner et al, 2004), and more evidence of this is provided here (Figures 3–7).

A large number of ice layers were present in the snowpack and were observed to have a complex effect on dye movement. Previous studies have identified three ways in which ice layers affect water movement through snow, namely the formation of static internal ponds above dips in ice layers, dynamic detention of flowing water, and diversion of flow along sloping ice layers (Langham, 1974a, 1974b). The role of ice layers within the snowpack at Haut Glacier d'Arolla, and changes through the season, are discussed below.

Percolation in snowpit sections

Observations throughout the season show that ice layers play an important role in influencing the movement of percolating meltwater, causing significant disruption and heterogeneity of flow patterns. On many occasions ice layers were observed to halt the downward movement of dye, with continued downward flow taking place from limited areas of the layer (Figures 3, 6 and 7). In Figure 3, 4 hours after dye injection the vast majority of dye is retained above a major ice layer 35cm from the snow surface. Beneath the ice layer dye has propagated downwards in just one location, while other areas of the snowpack show no evidence of percolation. Figure 6 also shows ice layers allowing restricted downward movement of dye, with flow taking place via multiple small flow fingers each around 1cm in diameter. Clearly, ice layers can be sufficiently impermeable to restrict downward movement of meltwater, but also allow water to pass through them at limited points. Ice layers were not observed to disintegrate in the presence of liquid water, as was suggested in early studies (Gerdel, 1954), but rather exhibited variable permeability as proposed by Langham (1974a), who showed theoretically that the size of veins between ice crystals, and therefore ice layer permeability, would respond continuously to changing temperature, pressure, and dissolved air concentration around the layer. A marked example of this is seen in Figure 4, which shows the retention of dye by a near-surface ice layer, in an area previously permeable to water flow, due to subsequent cold conditions. As the melt season progressed, ice layers in the remaining snowpack continued to play a role in retaining percolating meltwater, as seen in Figure 7. Notably however, there were fewer ice layers left in the snowpack as those closest to the surface had melted out during ablation, and their net effect is expected to be less significant.

Lateral redistribution of flow

In the sloping supraglacial snowpack at Haut Glacier d'Arolla the downslope diversion of percolating meltwater along ice layers appears to be widespread. In the first fluorometric experiment of the season, on 29th May, dye injected on the snowpack surface was seen to emerge in a pit 3 meters downglacier not at the snow-ice interface but along ice layers between 1.2 and 1.7m above the ice surface, in plumes 10–15cm wide. Clearly ice layers in the snowpack were sufficiently impermeable to deflect a significant amount of percolating meltwater over 3 meters downglacier. On 9th June, in an experiment at the same location, dye emerged along ice layers closer to the snowpack base, and in all later experiments dye was observed to arrive at the pit wall in the basal saturated layer, enabling detection using the borehole fluorometer. During the early melt season ice layers in the snowpack were clearly causing significant lateral redistribution of percolating meltwater, and this effect decreased through time.

Sideways excavations of surface dye injections show this effect more clearly. Figure x, taken on the 26th of June, shows the combined effect of deflection by multiple ice layers of varying sizes causing percolation through the snowpack to take place in a stepped fashion, reaching the base of the snowpack between 0.5 and 1m downglacier of the injection area on the surface.

Dye return curve shape, timing, and percolation rate derived from injections at the snowpack surface

Inspection of the shape and timing of dye return curves provides initial quantitative information about water movement through the snowpack. For Pit A (Figure 8), the transit time for dye movement through the snowpack shows a continuous decrease over the period of study, taking over 10 hours before maximum dye recovery in the earliest injection (June 14th, snow depth ~1.75m) and just 2 hours in the last injection (July 10th, snow depth ~0.60m). For injections at Pit B (Figure 9), the decrease in transit time is less consistent but shows the same trend. Deviations from the trend may be explained by the varying flux conditions under which dye injections took place. The rate at which water percolates through snow is expected, according to Colbeck's (1978) expression for the rate of propagation of a value of meltwater flux, to increase as the magnitude of the flux to the two-thirds power. Large values of flux therefore percolate faster than lower fluxes and water within the snowpack may accumulate with other percolating fluxes and travel at an increased rate. Flux inputs at the time of each dye injection were calculated from UDG records of surface lowering and the known volume of water added with dye. For experiments at Pit A, input fluxes generally decrease later in the season, such that the decrease in transit time seen in return curves can be expected to reflect a real (perhaps more marked) trend. Injections at Pit B took place under more variable flux conditions, possibly explaining the less consistent pattern of decreasing return time. The precise role of flux conditions cannot however be considered without undertaking further modeling of the interaction of percolating meltwater fluxes within the snowpack.

The asymmetric form of each return curve shows that water moves through the snowpack at a range of rates, typically resulting in a wide, dispersed return curve in earlier tests with a decrease in dispersion as the return curves become more peaked (Figure 8). In the earliest injections it frequently takes over 12 hours for the dye wave to pass the fluorometer; in later injections, although there may be a significant trailing limb as residual dye moves slowly through the snowpack, the majority of dye is recovered within 5 hours. This decrease in the dispersion of dye return curves, together with the marked decrease in transit time for dye movement through the snowpack, suggests that the snowpack becomes more efficient in its transmission of meltwater as the season progresses.

Mean percolation velocities (Tables 1 and 2) range between 0.13 and 0.49 mhr^{-1}, agreeing in general with previous estimates of percolation rates in snow (Jordan, 1983; McGurk and Kattelman, 1986; Fox et al., 1999). Further comparison to other reported values is impossible due to the varying flux conditions and snowpack stratigraphies under which observations would have taken place.

Trends in dye percolation rate

As discussed above, visual inspection of dye return curves suggests a change in snowpack hydrological behavior through the melt season. Trends in dye percolation rate were investigated by plotting scatter diagrams and considering the correlation between percolation rate and date of experiment for each pit. Results from Pit A show a significant (at the 95% level) increase in percolation velocity with time through the melt season (Figure 10). For the same pit, transit time for flow through the snowpack decreases as snow depth decreases (Figure 11) in a manner that is not simply proportional to decreasing snowpack depth but is best fitted by an exponential curve, suggesting an increase in the hydrological efficiency of the snowpack which explains the observed increase in percolation velocity. Results from Pit B exhibit poor correlations, likely due to the varying flux conditions under which injections were carried out.

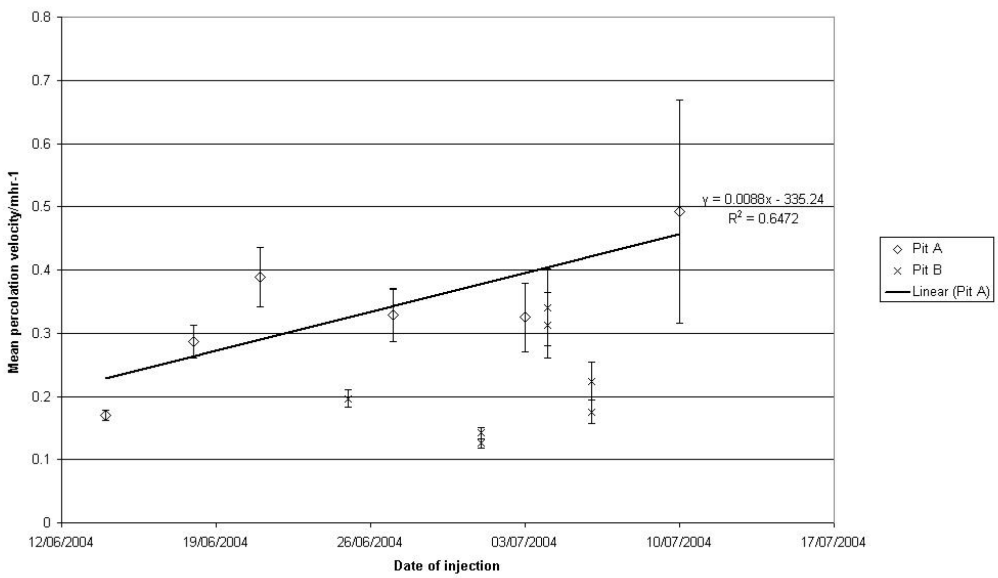

Figure 10: Scatter plot of percolation velocity against date of injection.

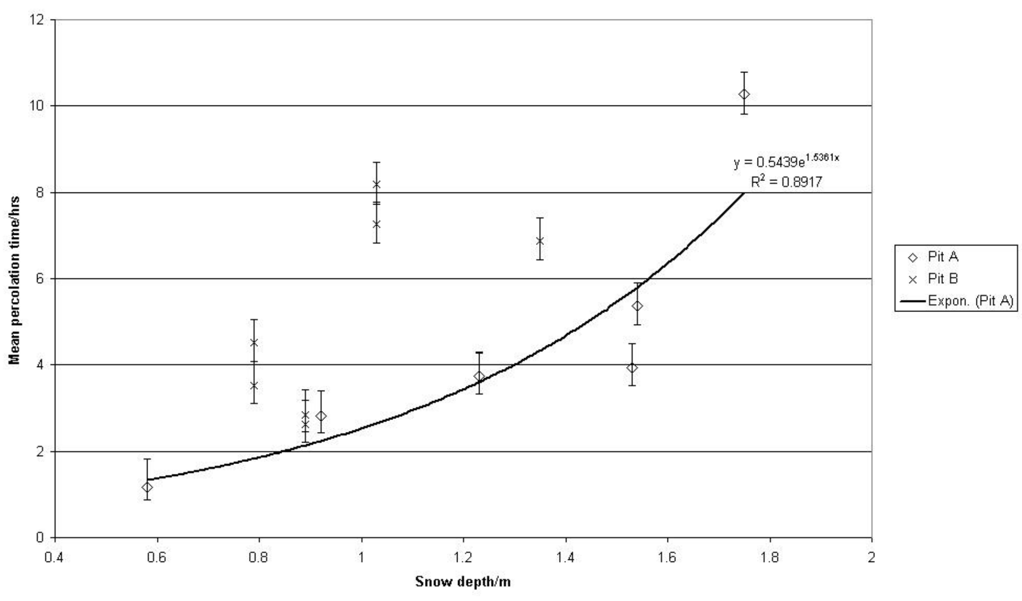

Figure 11: Scatter plot of percolation time against snow depth.

Snowpack permeability

The permeability of the snowpack is expected to be a principal factor controlling percolation. The increasing hydrological efficiency observed in the snowpack at Haut Glacier d'Arolla suggests an increase in snowpack permeability, probably tied to the decreasing effect of ice layers in restricting percolation. A change in snowpack density would also be expected to result in changing permeability; however, density measurements do not show conclusive proof of a change in density through the melt season. The wetting and compaction of the snowpack during the summer are generally expected (Male, 1980, p.368) to lead to an increase in density, and therefore decrease in permeability – the opposite effect from that seen here. Some increase of snow grain size, another possible cause of increasing snowpack permeability, was observed through the melt season, but it is difficult to quantify this change. In many areas the snowpack retained a very small (around 0.5mm) grain size for the duration of the melt season, suggesting that the influence of changing grain size on permeability would be minimal.

Equation 1, presented by Colbeck in 1978, represents our theoretical understanding of the rate of water percolation through snow and the factors controlling it:

$$dz/dt\big|_u = 3\alpha^{1/3}\, k^{1/3}\, \phi_e^{-1}\, u^{2/3} \qquad \text{Equation 1}$$

where $dz/dt\big|_u$ is the rate of water percolation through the snowpack, α is a constant representing the density and viscosity of water and gravitational acceleration, k is snowpack permeability, ϕ_e is effective snow porosity, and u is the volume flux of water. As $dz/dt\big|_u$ is known from dye injections, it is possible to calculate the permeability of the snowpack for each injection using Equation 1. Flux at the time of dye injections is known from ultrasonic depth gauge records of surface lowering together with the known volume of water added with each injection, and ϕ_e is derived from density measurements.

Colbeck's derivation of Equation 1 was based on the assumption of homogeneous percolation, which has been shown to be untrue for the snowpack at Haut Glacier d'Arolla (Figures 3 and 6). Despite this, application of Equation 1 is believed to give a useful estimate of net snowpack properties. Where percolation takes place via multiple preferential flow channels, flux within the snowpack, through those areas where flow is taking place is, on average, higher than that produced at the surface. The calculated k therefore provides a maximum estimate. In addition, although instantaneous flux at the time of each dye injection is used here, it must be remembered that due to the dependence of percolation velocity on flux magnitude, dye percolating through the snowpack is likely to encounter other percolating meltwater and thus the value of u used here is a minimum estimate of that actually traveling through the snowpack for most of its depth. The resulting k is again a maximum estimate. Although the calculated values of k are not expected to be correct in absolute value, they provide a useful opportunity for comparing the permeability values found and used in other studies with the situation observed at Arolla. The calculated estimates of k are plotted in Figure 12 against the date of the experiment from which they were derived.

The calculated values of k are in general low in comparison to those found in other studies. Fox et al. (1999) obtained values of k ranging between $3.2\text{x}10^{-8}$ and $6.57\text{x}10^{-6}$ cm^2 from lysimeter data collected in a continental alpine snowpack in the Colorado Front Range, USA, stating that their results were in general over an order of magnitude smaller than minimum values of k reported elsewhere. The same is true of k values reported here.

Modeling studies of water percolation through snow have frequently based their estimates of k on the formulation of Shimizu (1970), in which k depends on snow grain size d and snow density ρ_s according to the formula

$$k = 0.077d^2\exp[-7.8(\rho_s/\rho_w)] \qquad \text{Equation 2}$$

(where ρ_w is the density of ice). Although useful when working in relatively homogeneous snow, this method of estimating permeability does not take into account the presence of low permeability ice layers frequently found within the snowpack and widely present at Haut Glacier d'Arolla, which will result in lowering of net snowpack permeability. Even the estimation of permeability by Shimizu using a grain size of 0.5mm, generally expected to be found in early-season, hydrologically poorly-developed snowpacks, results in a value (1.79×10^{-6} cm^2) significantly higher than those found here. The straightforward application of Shimizu's formula for the estimation of snowpack permeability is therefore insufficient where the snowpack contains ice layers or other less permeable strata, as is frequently the case in alpine glacial snowpacks.

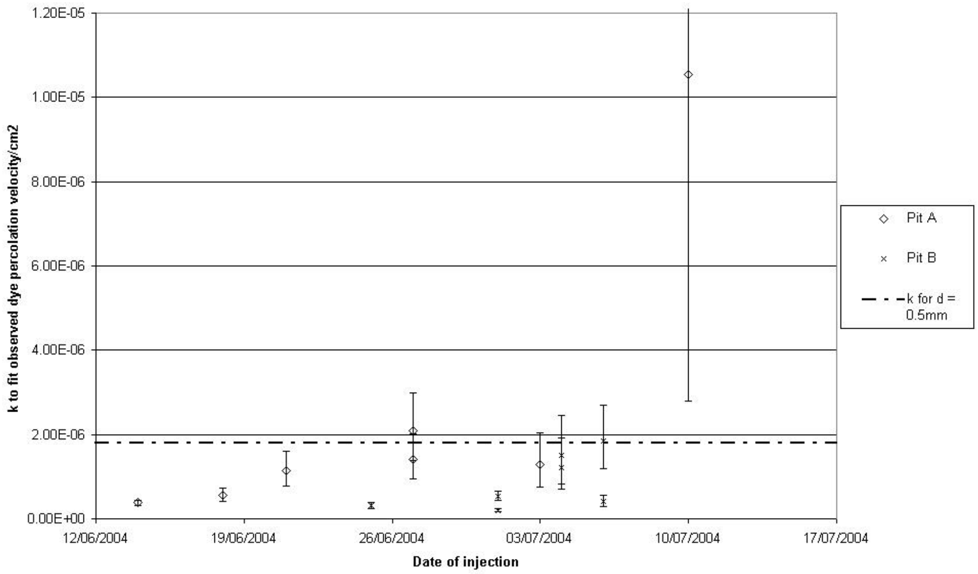

Figure 12: Scatter plot of *k* against date of injection. Dashed line indicates the value of *k* calculated by Shimizu (1970) for snow with a grain diameter of 0.5mm.

CONCLUSIONS

Whilst the links between supraglacial snowpack hydrology and glacier dynamics could not be considered here, investigations in the supraglacial snowpack provided useful information on its changing hydrological behavior during the melt season. Flow patterns were seen to be highly heterogeneous early in the season, due to the influence of ice layers restricting percolation. The changing form of dye return curves and increasing dye percolation rates suggest an increase over the course of the melt season in the efficiency with which the snowpack transmits meltwater, and this is confirmed by the increase in net snow permeability calculated from percolation velocities. Permeability values are significantly lower than those frequently used in modeling studies of snow hydrology, and show the need to consider the influence of low permeability ice layers rather than assuming homogeneous snowpack properties. The changing hydrological efficiency of the supraglacial snowpack is likely to play an important role in controlling discharge into the rest of the glacier hydrological system, and this effect can only be understood by considering the heterogeneous nature of percolation through the snowpack and its evolution through time.

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