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ABSTRACT. Water levels were measured in boreholes spaced along the entire length of Bench Glacier, Alaska, USA, for a period in excess of 2 years. Instrumented boreholes were arranged as nine pairs along the center line of the glacier and an orthogonal grid of 16 boreholes in a 3600 m^2 region at the center of the ablation area. Diurnal fluctuations of the water levels were found to be restricted to the late melt season. Pairs of boreholes spaced along the length of the ablation area often exhibited similar fluctuations and diurnal changes in water levels. Three distinct and independent types of diurnal fluctuations in water level were observed in clusters of boreholes within the grid of boreholes. Head gradients suggest water did not flow between clusters, and a single tunnel connecting the boreholes could not explain the observed pattern of diurnal water-level fluctuations. Inter-borehole and borehole-cluster connectivity suggests the cross-glacier width of influence of a segment of the drainage system connected to a borehole was limited to tens of meters. A drainage configuration whereby boreholes are connected to a somewhat distant tunnel by drainage pipes of differing lengths, often hundreds of meters, is shown with a numerical test to be a plausible explanation for the observed borehole behavior.

INTRODUCTION

Water at the bed of a glacier strongly influences the motion of the glacier through basal sliding (Paterson, 1994; Willis, 1995). Though no predictable relationship between water and sliding velocity has been determined, an increase in sliding speed is often attributed to increased subglacial water pressure (e.g. Iken and others, 1983; Iken and Bindschadler, 1986; Jansson, 1995; Fountain and Walder, 1998; Sugiyama and Gudmundsson, 2004). Studies linking water pressure and sliding have relied on measurements of the water level in boreholes intersecting the bed as proxy measures of basal water pressure (e.g. Engelhardt and others, 1978; Iken and Bindschadler, 1986; Jansson, 1995; Iken and Truffer, 1997; Sugiyama and Gudmundsson, 2004). Owing to difficult field logistics, much of our understanding of subglacial pressure variations is based on studies utilizing a small number of boreholes and intervals restricted to periods of the ablation season (e.g. Jansson, 1995; Sugiyama and Gudmundsson, 2004). Typically, only boreholes with low water levels and/or large daily swings in water level have been considered ‘connected’ to the subglacial hydrology system and to be representative of a relevant basal water pressure (e.g. Iken and Bindschadler, 1986; Jansson, 1995). As borehole measurements are a key tool for investigating the linkage between subglacial water flow and glacier sliding, it is critical to understand the interactions between the subglacial drainage system and the borehole water-level variations we measure.

Direct observations, dye-tracing experiments and borehole investigations suggest the basal drainage system develops from a distributed system of cavities in the beginning of the melt season to a more channelized system as the melt season progresses (i.e. Fountain, 1993; Sharp and others, 1993; Fountain and Walder, 1998; Nienow and others, 1998; Harper and others, 2002). Diurnal fluctuations are a dominant characteristic of summer borehole water levels and have been attributed to connections to the channelized drainage system (Iken, 1972; Rothlisberger and others, 1979; Iken and Bindschadler, 1986; Fountain, 1994; Meier and others, 1994; Hubbard and others, 1995; Smart, 1996; Gordon and others, 1998; Harper and others, 2002). Investigations on South Cascade Glacier, Wahington, USA, (Fountain, 1994) and Haut Glacier d’Arolla, Switzerland, (Hubbard and others, 1995; Gordon and others, 1998) both concluded that the diurnal fluctuations observed in borehole arrays a few hundred meters wide were caused by a single large drainage tunnel alternating between pressurized and unpressurized states. Murray and Clarke (1995) and Gordon and others (1998) observed that peak water level in connected boreholes corresponded with water-level minimums in boreholes unconnected to the channelized drainage system. Despite the progress made by these studies, the configuration of the drainage system and whether boreholes allow an accurate measure of basal water pressure remains only weakly understood.

Here we present observations of borehole water levels over a period spanning the entire ablation season and from locations along the full length of Bench Glacier, Alaska, USA. Over two consecutive summer seasons, 43 boreholes were drilled and instrumented in pairs along the length of the glacier and in a 4×4 grid of boreholes in the center of the ablation area. Observations were recorded continuously for both the initial season when the boreholes were drilled, and subsequent seasons after the winter cold wave had frozen the tops of the boreholes shut. In other work we have described spring conditions leading to the onset of diurnal variations (Harper and others, 2005) and the termination of diurnal variations during late fall (Fudge and others, 2005). In this paper, we focus on temporal and spatial patterns of diurnal

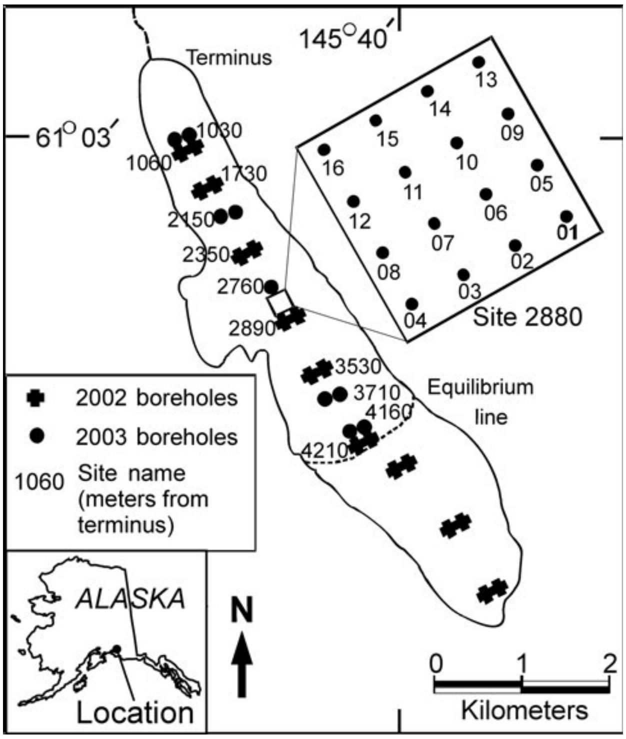

Fig. 1. Map of Bench Glacier, Alaska, showing boreholes drilled in 2002 (crosses) and in 2003 (circles). Site names are the distance (in meters) from the terminus. The enlargement of the 16-borehole grid is oriented with the map. Boreholes 1–4 are the most up-glacier.

fluctuations in water level which are the dominant characteristic of summer water-level variations. We show that large head gradients exist between boreholes with in-phase diurnal fluctuations in water level and propose a new interpretation of the late-summer subglacial drainage system.

DATA COLLECTION

Bench Glacier

Bench Glacier is a temperate glacier located in the Chugach Mountain Range of south central Alaska. The glacier is approximately 7 km long and spans 1000 m vertically. The terminus is located at an elevation of 1100 m, and the equilibrium-line altitude is about 1400 m (Fig. 1). Bench Glacier has a simple geometry with no major tributaries. The average surface slope is about 10°, with one steeper section of 20–30° just above the equilibrium line. One major stream exits the glacier at the terminus. Over 600 moulins were mapped (Reeve, 2006) throughout the ablation area. The vast majority were low-discharge (5×10^{-5} to $8 \times 10^{-3}\,m^3\,s^{-1}$), but the largest 10% of moulins contributed 90% of the meltwater and just three moulins contributed approximately 50% (Reeve, 2006).

Radar profiles of the bed show the depth of the glacier increases up-glacier throughout the ablation area to a maximum of about 200 m at the equilibrium line. The bed has a parabolic cross-section without major riegels, an average slope in the ablation area of 3.5° and no major overdeepenings (Bradford and Harper, 2005). We characterize the bed as 'hard', based on observations in >50 boreholes including penetrometer tests, borehole video imaging, and careful monitoring of the drill tip as it encountered the bed. While till may be locally thick (i.e. meters) in patches, or more widespread and thin (i.e. decimeters), evidence is lacking for a thick, widespread till layer, implying that basal dynamics hinge on ice–rock interactions and not ice–till interactions.

Borehole observations

Forty-three boreholes were drilled to the bed (140–190 m) and instrumented during spring of 2002 and 2003. Borehole sensors were functional for varying lengths of time, and many of the boreholes yielded ≥2 years of continuous data. In 2002, nine pairs of boreholes were drilled and instrumented. The pairs were evenly spaced at sites along the center line between the top of the accumulation area and the bottom of the ablation area (Fig. 1). In 2003, four additional pairs of boreholes, a 16-borehole grid (Fig. 1), and a single borehole 100 m below the grid were installed at sites in the ablation area. The spacing between all boreholes at each site was 20 m.

The boreholes were drilled with hot-water methods during May and early June, when the glacier was covered with snow. When the drill failed to advance, and was at the bed as determined by radar measurements, it was reversed and readvanced repeatedly in an effort to penetrate possible englacial debris. We assume the boreholes to be nearly vertical, based on inclinometry measurements of boreholes drilled by the same equipment and methods (Harper and others, 1998). The tops of the boreholes were left open to the atmosphere. A 1 m long perforated PVC rod was attached to a Honeywell 40PC series pressure transducer (250 psi), causing it to sit above the bed. Each pressure transducer was connected to a data logger at the surface. The data loggers used in 2002 recorded water-level measurements every 15 min, while those used in 2003 made measurements every 5 min.

Terminology

Diurnal fluctuations in water level can be difficult to define precisely in real data because water levels often show a wide spectrum of variations that span a range of periods including a 24 hour cycle. We define diurnal fluctuations in water level in the context of this paper as daily swings in water level that are <5 m in magnitude and repeat for three or more consecutive days. Fluctuations that were superimposed on longer-term water-level trends were included.

Each borehole is named by the site and either a number or a letter. The site names are the distance in meters from the glacier terminus so that position on the glacier is summarized in the name. The 16-borehole grid is site 2880; boreholes here are identified by a number, starting in the upper left corner as viewed looking up-glacier. The boreholes at other sites are designated either 'E' or 'W' for the east or west side of the center line, respectively. For example, BH 2350-E is located 2350 m up-glacier from the terminus and is on the east side of the glacier center line.

In this paper, the water levels are presented as meters above sea level (m a.s.l.), allowing hydraulic gradients between boreholes to be compared easily. The precision of the transducer measurements was 10 cm of water height, but the overall error increased as the borehole was advected over different subglacial topography. We estimate the errors could reach 3 m by the end of the melt season if the post raising the pressure transducers off the bed failed and the subglacial topography was rough. The actual error was likely much smaller than this. Nevertheless, the large

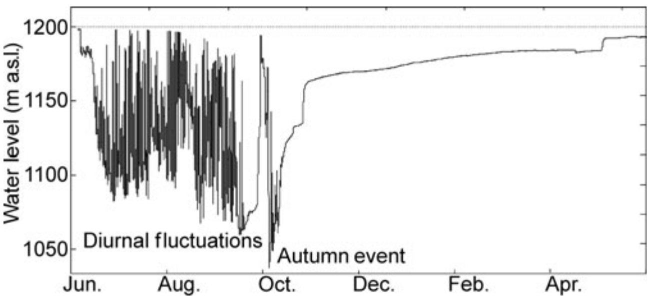

Fig. 2. Year-long water-level record from borehole 2150-E beginning in June 2003 when the borehole was drilled. Straight line is the glacier surface. The large diurnal water-level fluctuations of summer and the high stable pressure of winter are shown. The autumn event is common to many boreholes after diurnal fluctuations in water level have ended, and is discussed more by Fudge and others (2005).

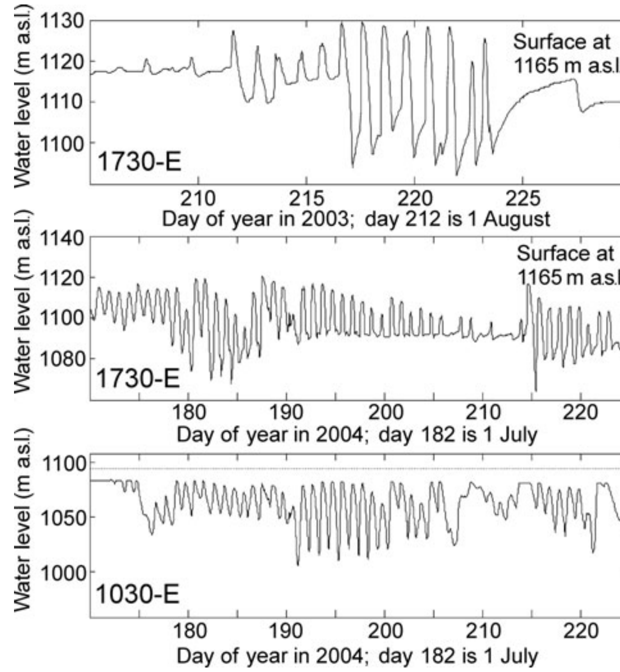

Fig. 3. Diurnal water-pressure records from boreholes in the second year of operation. The tops of the boreholes have frozen shut during the winter cold wave.

diurnal variations in water level and head gradients we address here (tens of meters) are not significantly impacted by these errors.

RESULTS

The continuous multi-year water-level records reveal a distinct difference between the melt and winter seasons. Throughout winter, the water levels are generally high and slowly varying, with subdued variations over week- to month-long timescales (Fig. 2). The melt season, in contrast, is characterized by lower average and rapidly varying water levels and is often dominated by large, diurnal fluctuations in borehole water level. Diurnal fluctuations in borehole water level occurred during individual study years for periods ranging from a few days to over 90 days in individual boreholes. The initiation of diurnal fluctuations on Bench Glacier began in spring with an approximately 2 week synchronous decline in water level along the entire ablation area (Harper and others, 2005). The termination of diurnal fluctuations occurred in individual boreholes throughout the ablation season, but diurnal fluctuations rarely existed past September (Fudge and others, 2005).

Diurnal fluctuations were common in borehole water-level records from the ablation area but were not observed in the accumulation area. Diurnal fluctuations were also observed in both the first season of drilling when the boreholes were open to the surface, and in subsequent seasons after instruments had been in place for more than a year and the winter cold wave had frozen the upper part of the boreholes shut. Many of the sensors were damaged over time, resulting in far fewer working sensors in boreholes that were $\geq$1 year old. Of the open (newly drilled) boreholes, 7 of 10 (70%) had diurnal fluctuations in 2002, and 15 of 25 (60%) had them in 2003. Boreholes were less likely to record diurnal fluctuations after they had been frozen shut at the surface. In 2003, 2 of the 6 (33%) frozen boreholes with functional sensors had diurnal fluctuations in water level, and in 2004, 3 of the 13 (23%) frozen boreholes had diurnal fluctuations in water level.

Diurnal fluctuations in boreholes older than 1 year (and frozen closed at the surface) are shown in Figure 3. These records indicate that diurnal fluctuations in water level exist even without surface water input or subglacial drainage connections enhanced by hot-water drilling methods. The frozen tops do not preclude water input from englacial sources, and the lower percentage of boreholes exhibiting diurnal fluctuations may result from more limited water input and a lack of drilling-induced connections at the bed. Hence, the records from frozen-closed holes indicate that diurnal fluctuations in water level are not merely artifacts of drilling, but they also suggest that diurnal pressure fluctuations at the bed may be less widespread than borehole observations in the year of drilling imply.

Borehole water levels in 2002

The water-level records from four sites in the ablation area during 2002 are shown in Figure 4. The timing and magnitude of diurnal fluctuations in the two boreholes at site 4210 matched closely for more than 3 weeks (days 179–204). Diurnal fluctuations of water level in boreholes at site 2350 also closely matched each other, though only for a 7 day period (days 211–217) after diurnal fluctuations in water level began suddenly at borehole 2350-E.

The diurnal fluctuations of water level in the two boreholes at site 1730 differed in character. Borehole 1730-E had more typical 'sinusoidal' diurnal fluctuations in water level, and the fluctuations in borehole 1730-W occurred as spikes above a baseline water level. The fluctuations were in phase between the two boreholes, but water flow was not directed from borehole 1730-E to 1730-W because the water level in borehole 1730-E was always below the water level in borehole 1730-W. The type of diurnal fluctuation observed in borehole 1730-W was not observed in any other borehole in either season. The water level rarely fell below 130 m above the bed (1440 m a.s.l.), suggesting an englacial connection may have occurred at this level in the borehole.

At site 2890, diurnal fluctuations in water level were observed in borehole 2890-E but not at borehole 2890-W. The water level did vary in borehole 2890-W but on a cycle much faster than daily, often with a 6 hour period. The

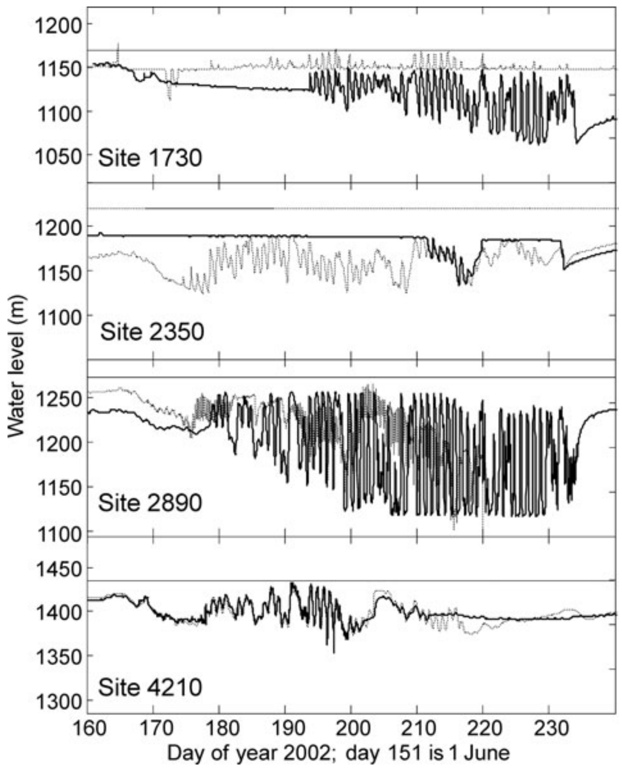

Fig. 4. Borehole water-level records from four sites in the ablation area in 2002. Eastern boreholes (E) are solid lines, and western boreholes (W) are dashed lines. Horizontal line is the glacier surface. The records of sites 2350 and 4210 can be difficult to distinguish from each other because the water levels match closely.

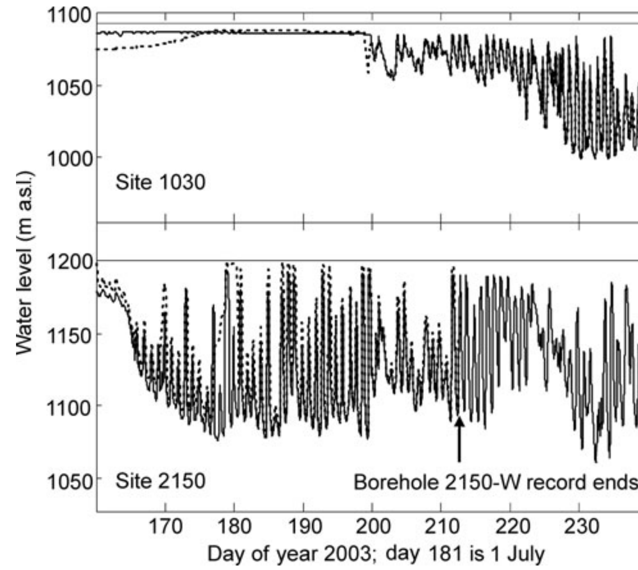

Fig. 5. Borehole water-level records from two sites in the ablation area in 2003. Eastern boreholes (E) are solid lines and western boreholes (W) are dashed lines. Horizontal line is the glacier surface. Records can be difficult to distinguish from each other because water levels match closely.

swings are thought to be real and not a sensor malfunction, but we do not have a simple explanation for why the water level varied so rapidly. Neither borehole at site 3530 experienced diurnal fluctuations in water level, and neither is shown in Figure 4.

Borehole water levels in 2003

Significant diurnal fluctuations occurred at the lower two sites installed in 2003 (Fig. 5). At site 1030, the diurnal fluctuations in water level in the two boreholes matched each other closely. The same was true of the pair of boreholes at site 2150. The diurnal fluctuations at site 1030 did not begin until midsummer, more than a month after diurnal fluctuations had begun elsewhere on the glacier. The initiation of diurnal fluctuations at this site began with a sudden drop in water level.

The water-level records from site 2880, the 16-borehole grid, are presented in Figure 6. The initiation of diurnal fluctuations in the borehole grid at site 2880 did not begin until after a period of synchronous water-level variations among all boreholes at the site. Small initial variations at the beginning of summer were followed by a 2 week decline in water level from day 163 to day 176 (Fig. 6). After the decline, the boreholes no longer exhibited uniform variations, and a majority began diurnal fluctuations for at least a short period, though the character and magnitude of the fluctuations varied considerably between boreholes. Harper and others (2005) describe the water-level variations prior to the onset of diurnal fluctuations in more detail. Many boreholes had diurnal fluctuations in water level from day 179 to day 183 that were associated with larger trends throughout the grid. After day 183, boreholes only terminated fluctuations. The relationships between boreholes with diurnal fluctuations in the grid area are complex and are discussed in more detail below.

Borehole grid

Head gradients

Large head gradients between boreholes in close proximity to each other have been observed on many glaciers (e.g. Fountain, 1994; Hubbard and others, 1995; Murray and Clarke, 1995; Smart, 1996; Gordon and others, 1998). They typically exist when at least one borehole has a water level that varies only slightly and is considered isolated from (or unconnected with) the channelized drainage system. Alternatively, boreholes exhibiting diurnal fluctuations in water level typically have either closely matching water levels or reversing head gradients (e.g. Fountain, 1994; Hubbard and others, 1995; Gordon and others, 1998), implying connection of the different boreholes to the same segment of channelized drainage system.

On Bench Glacier, we observed the expected large head gradients between boreholes with steady water levels (e.g. 2880-06 and -07, particularly days 175–190), and also between boreholes with diurnal fluctuations and boreholes with steady water levels (e.g. 2880-02 and -06). Matching water levels in boreholes with diurnal fluctuations in water level were also recorded (e.g. 2880-04 and -11, days 180–200, though this behavior is also shown outside the grid, particularly at sites 1030 and 2150; Fig. 5). However, we also recorded large and persistent head gradients between boreholes exhibiting diurnal fluctuations in water level. An example from two boreholes located 40 m apart in the grid area is shown in Figure 7. There is one borehole in between the two which shows a high stable water level for most of the record.

A cross-correlation analysis of these records with hourly time lags from +24 to –24 indicates the fluctuations were in phase. With the water levels rising and falling in synch while

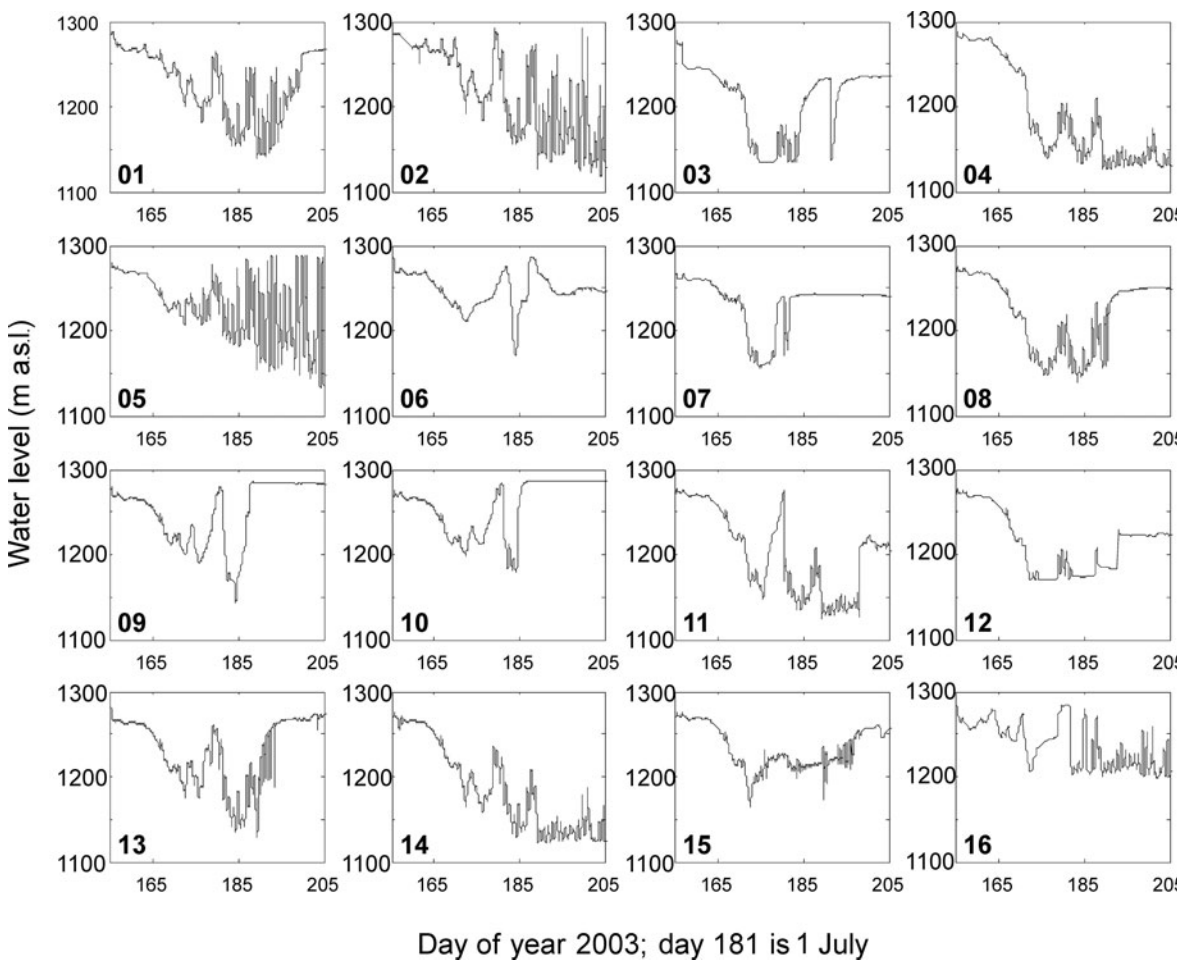

Fig. 6. Borehole water-level records from the 16 boreholes at site 2880, oriented looking up-glacier with boreholes 1–4 highest on the glacier and boreholes 1, 5, 9 and 13 on the east. Glacier surface is at 1285 m a.s.l.

the large head gradient is maintained, water is not flowing between the boreholes. If water were to flow between them through a small channel, the volume of water needed to be moved to create the diurnal fluctuations in water level would cause an unstable jökulhlaup-type condition (Nye, 1976) under the large head gradients.

Cluster analysis

To better elucidate the spatially and temporally complex relationships between the 16 boreholes in the grid, we used a cluster analysis to identify groups of boreholes exhibiting similar water-level variations. The k-means clustering approach (Hartigan, 1975) used the borehole water levels at each time-step (5 min resolution was used) to partition the observations into mutually exclusive clusters by minimizing the square of the differences between borehole water level and the mean water level for each cluster and all clusters as a whole. The analysis requires an initial assumption of the number of clusters and then groups one or more holes into each cluster based on water-level variations. It does not determine the strength of the relationship between boreholes within a cluster. In our case, the analysis was performed for all reasonable numbers of clusters (four to eight), and each analysis yielded similar groupings of holes. Here we present the analysis based on five clusters.

A first clustering analysis was done for days 175–200, a period when the majority of boreholes had at least one episode of diurnal water-level fluctuations (Fig. 8a). This analysis yielded clusters 1, 2 and 3 composed of boreholes with diurnal fluctuations in water level, and clusters 4 and 5 composed primarily of boreholes without diurnal fluctuations in water level (cluster 4 included one borehole with

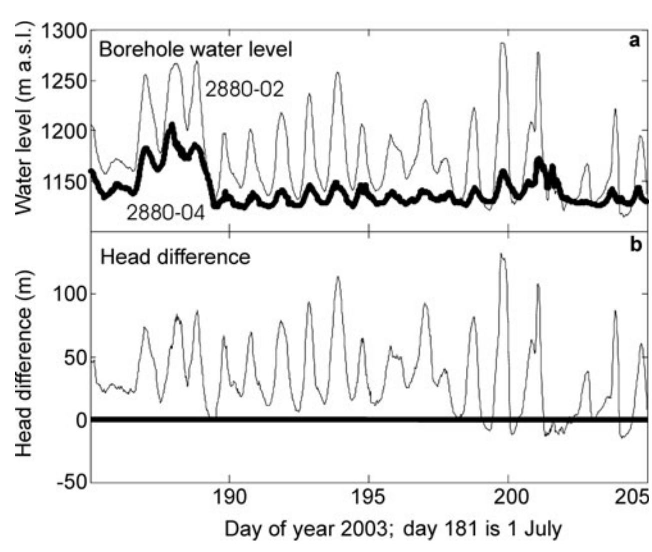

Fig. 7. (a) Water-level records of boreholes 2880-02 and 2880-04. (b) Head difference between boreholes 2880-02 and 2880-04.

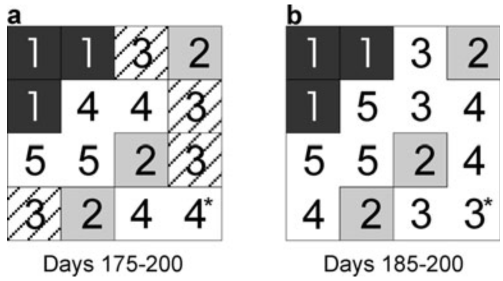

Fig. 8. Statistical clusters of boreholes in the grid (site 2880), oriented looking up-glacier. The numbers designate which cluster a borehole belongs to. Shaded and hatched clusters indicate the cluster composed of only boreholes with diurnal fluctuations. (a) Clustering from day 175 to day 200. (b) Clustering from day 190 to day 200. Asterisk (*) indicates borehole had diurnal fluctuations in water level but was not clustered with other boreholes with diurnal fluctuations.

diurnal fluctuations). Each borehole of cluster 3 is adjacent to a borehole from cluster 2.

A second cluster analysis was performed for days 185–200. Clusters 1 and 2 were unchanged for this period. Cluster 3 consisted of different boreholes in the second clustering analysis (Fig. 8b) because the holes in cluster 3 from the first analysis had ceased diurnal variations prior to day 185 and thus had lost their spatial coherence. The clustering of boreholes lacking diurnal fluctuations does not necessarily imply a strong relation between them: they simply fail to show the similar variations.

Spatial relationships

The head difference discussed above (Fig. 7) between boreholes 2880-02 and 2880-04 is representative of the head gradients between boreholes of clusters 1 and 2. This is shown in Figure 9 where the records from boreholes 2880-02 and 2880-04 have been re-plotted with an additional borehole from each cluster. The diurnal water-level fluctuations from boreholes 2880-16 are also plotted, and the low- amplitude, high mean water-level fluctuations show why this borehole was not clustered with any of the other boreholes with diurnal fluctuations. The three distinct types of fluctuations are clearly visible: (1) high amplitude (cluster 1); (2) low amplitude, low mean water level (cluster 2); and (3) low amplitude, high mean water level (borehole 2880-16). The diurnal fluctuations in water level were in phase among the clusters. Water was not flowing between the clusters based on head gradients, for the same reasons described above for the boreholes of Figure 7. The three distinct types of diurnal fluctuations in water level suggest each set was connected to a separate segment of the channelized drainage system.

The locations of the clusters make it possible to determine the width of the glacier affected by a segment of the glacier drainage system. The boreholes of cluster 2 are bounded to the southeast by cluster 1 and to the northwest by borehole 2880-16. The distance between boreholes 2880-05 and 2880-16 is 72 m, indicating that the drainage segment connected to the boreholes of cluster 2 affects an area no wider than this. In fact, it is probably less because the boreholes in between without diurnal fluctuations are not connected to the same drainage segment as the boreholes of cluster 2.

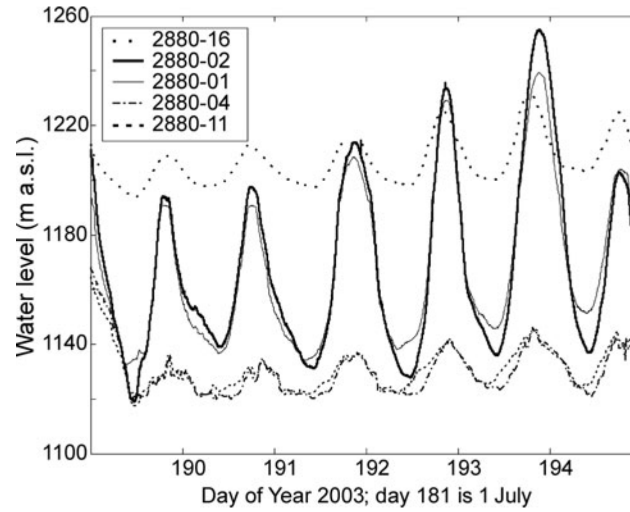

Fig. 9. Diurnal water-level fluctuations in five boreholes illustrate the three distinct types observed at site 2880 (the 16-borehole grid). Boreholes 01 and 02 are in cluster 1 (solid lines), boreholes 04 and 11 are in cluster 2 (dashed lines), and borehole 16 is not clustered with other boreholes with diurnal fluctuations (dotted line).

DISCUSSION

The characteristics of diurnal water-level fluctuations presented above give insight into the configuration of the drainage system of Bench Glacier. These observations will be compared with previous observations and interpretations and used to develop and test a new conceptual model for subglacial water flow. Before continuing, it is important to clarify our descriptive terms for various elements of the drainage system. 'Tunnel' is used to describe large-discharge drainage channels and may be regarded in a Röthlisberger sense as a pathway that drains a significant area of the glacier and is at a lower pressure than ice overburden. 'Pipe' is used for low-discharge channels that drain to tunnels.

The borehole water-level records at Bench Glacier show a high degree of correlation at the beginning of the melt season, implying a relatively uniform, distributed basal water system (Harper and others, 2005). The uniform pressure field ends after a 2 week decline in borehole water levels. At site 2880 (the 16-borehole grid), the similarity in water-level records diminished until the three clusters of boreholes became apparent. The decrease in connectivity between boreholes suggests the development of a more channelized drainage system. It is commonly believed that the drainage system evolves from a well-connected linked cavity system at the beginning of the melt season to an arborescent channelized drainage system as the amount of melt increases towards the middle of the season (Fountain and Walder, 1998). Our observations support such a progression, though they suggest that the channelized system has a significantly different topology and characteristics than are commonly assumed.

Englacial influences on water-level records

The drilling of boreholes has revealed that englacial passages are common in temperate glaciers, but the geometry and distribution of them is poorly understood (e.g. Fountain, 1994; Harper and Humphrey, 1995; Fountain and Walder, 1998; Gordon and others, 2001; Fountain and others, 2005). McGee and others (2003) have observed water flow from a borehole to an englacial passage with borehole video, and Fountain and others (2005) have imaged an englacial passage with radar. The water-level record from borehole 1730-W (Fig. 4) is an example of a borehole with a probable englacial connection. The water level has daily increases, but rarely drops below 1440 m a.s.l. (130 m above the bed), suggesting an englacial passage intersects the borehole at this level.

In the other water-level records, the presence of englacial passages is not obvious, but neither can it be ruled out. We believe the majority of records are driven by subglacial connections because similar water-level fluctuations are observed in multiple boreholes: the near-matching water level in pairs of boreholes along the length of the glacier, the clusters of boreholes in the grid with distinct diurnal fluctuations in water level, and the glacier-wide 2 week decline in water level at the beginning of the melt season. Also, many of the boreholes have low minimum water levels which suggest that either they are connected at the bed, or an englacial passage is located near the bed. Both Harper and Humphrey (1995) and Fountain and others (2005) observed that englacial passages are steeply dipping, implying the englacial passages connect quickly with the subglacial drainage system.

Comparison with other borehole arrays

During the course of summer, the subglacial drainage system is believed to develop into an arborescent channel network (Fountain and Walder, 1998). Studies using borehole arrays on South Cascade Glacier (Fountain, 1994) and Haut Glacier d'Arolla (Hubbard and others, 1995) both proposed a similar model whereby diurnal fluctuations of borehole water levels are caused by basal water propagation from a large drainage tunnel. Head gradients at the bed adjacent to the tunnel (where boreholes were assumed to connect) reverse as the main tunnel becomes pressurized and unpressurized on a diurnal cycle and the magnitude of the water-level fluctuations in the boreholes dissipates as the boreholes are farther away from the tunnel. Murray and Clarke (1995) showed that load transfer on Trapridge Glacier, Yukon, Canada, occurred when pressure in the channelized system was high, causing a decrease in water level in unconnected boreholes. This was also observed with further study at Haut Glacier d'Arolla (Gordon and others, 1998). In these studies, observations supported the presence of a single tunnel driving water-level fluctuations in the borehole arrays that spanned 250–400 m in glacier width. This model, however, is not consistent with observations on Bench Glacier. We must somehow explain both the matching water levels observed in pairs of holes along the length of the ablation area and the clustering of boreholes in the grid area where groupings exhibited in-phase diurnal fluctuations but with different magnitude and water levels.

Conceptual model

Here, we develop a conceptual model to explain the diurnal water-level fluctuations observed on Bench Glacier. We note that our description is not uniquely determined by the data, but we believe it to be the simplest plausible explanation. A diagram showing our interpretation of the configuration of the subglacial drainage system is depicted in Figure 10. For clarity, only the drainage system of borehole clusters 1 and 2 is included in the diagram. In the conceptual model, water from the surface is delivered to the bed by a moulin where it then flows through a drainage pipe to a tunnel. The water in the pipe is at a higher pressure than water in the tunnel because of the direction of water flow. A separate drainage pipe connects to each cluster of boreholes with similar diurnal water-level fluctuations. Each pipe develops an independent pressure regime, allowing the large head gradients between boreholes of different clusters to persist. The boreholes in the grid without diurnal fluctuations in water levels are isolated from the pipes and do not directly connect to the channelized drainage system.

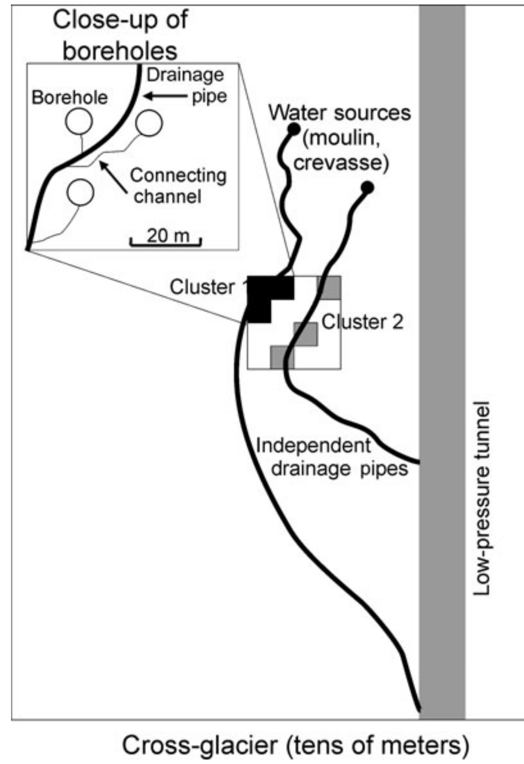

Fig. 10. Conceptual model proposed for the diurnal fluctuations in water level observed on Bench Glacier. Boreholes connect to a drainage pipe which is fed by a water source (i.e. moulin, crevasse) and drains to a subglacial tunnel. The pipes develop their own pressure regimes.

The diagram in Figure 10 suggests that the channelized drainage system does not branch evenly in the cross-glacier and down-glacier directions. Instead, the pipes remain independent of each other for long distances down-glacier and do not coalesce into gradually larger discharge channels. The configuration also implies that pressure variations in the major drainage tunnel are not the dominant forcing for water-level fluctuations in the boreholes. In our view, the borehole water-level fluctuations are the result of the joint behavior of the pressure regimes in the pipes, the tunnel pressure fluctuations and, to a limited extent, the individual connections of boreholes to pipes.

For individual pressure regimes to develop in drainage pipes, the pressure in the tunnel cannot be affected significantly by water input from the pipes. This will only be true if the water contribution by the pipes is much smaller than the discharge already in the tunnel. At Bench Glacier, Reeve (2006) found that just three moulins accounted for approximately half of the surface water input which, albeit with large measurement uncertainty, was also half of the discharge in the outlet stream. All three of the moulins were located above the 16-borehole grid. Reeve (2006) also used dye-tracing

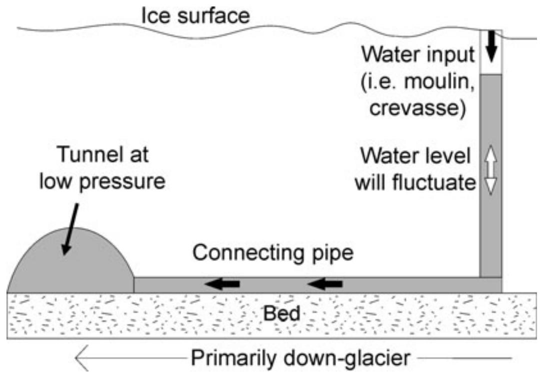

Fig. 11. Schematic of model set-up for numerical test. The water level will fluctuate in the moulin based on the pressure in the pipe and serves as a proxy for the water level in a connected borehole.

experiments to show that water delivered to the bed by these moulins flowed through the glacier quickly ($\sim$0.4 m s^{-1}) in conduit-like flow. These observations suggest that it is plausible for the discharge in the drainage tunnel to be much greater than the input from individual drainage pipes. The numerical test below will be used to further develop characteristics of a moulin–pipe–tunnel drainage configuration.

While it is possible that water flow into a borehole could create its own drainage pipe, this did not appear to be common at Bench Glacier. First, boreholes often had nearly matching diurnal water-level fluctuations, suggesting the boreholes were connected to the same drainage pipe. Second, three boreholes (1030-E, 1030-W, 2350-W) began diurnal fluctuations with a rapid initiation well into the melt season, implying that a pipe with diurnal pressure fluctuations already existed. Finally, direct observation of the tops of the boreholes found that water flow into holes was not common.

A numerical test

Model set-up

To test the plausibility of diurnal fluctuations caused by small discharge pipes and to further investigate the spatial extent of drainage network components, we developed a simple numerical model of a moulin–pipe–tunnel coupled system. The configuration of the drainage system was simplified from the conceptual model by simulating only a moulin–pipe–tunnel system (i.e. no borehole) and is shown in Figure 11. This was done to avoid the complex modeling of water flow directed both to and from a borehole. The amplitude of the water-level fluctuations in the moulin provides insight into the feasibility that a moulin–pipe–tunnel drainage system configuration could produce the observed diurnal fluctuations in borehole water level.

In the numerical model, the moulin is considered to be a vertical shaft with a set diameter that has a water level corresponding to the pressure in the pipe. In this configuration, water drains continuously from the moulin through the pipe to the tunnel. The water input to the moulin varies smoothly on a diurnal cycle and is the only water source considered. The pressure in the tunnel is considered to be unaffected by the water input from the pipes. This assumption is justifiable, as discussed above, based on the large percentage of water input to the glacier by a small number of moulins. The tunnel is considered to have constant and low pressure. We recognize that a subglacial tunnel is unlikely to be at a constant pressure for much of the melt season, but treating it as constant allows the magnitude of fluctuations in the pipe to be determined. A more detailed discussion of the tunnel pressure follows the modeling results below. The effect of diurnally varying water flow, and hence pressure, in the tunnel is to increase the pressure in the pipe by the amount in the tunnel, magnifying the diurnal fluctuations in the pipe.

The physics governing the transient flow of water in a subglacial conduit has been developed by Nye (1976) and Spring and Hutter (1981). We have simplified these equations by making one additional assumption: that discharge is constant along the entire length of the pipe. This assumption is valid if the change in discharge from melting the pipe walls is small, the time for the water to flow through the pipe is short such that the discharge at the upper boundary is similar to the discharge at the lower boundary, and the amount of water being added to the pipe is small. Nye (1976) found that the change in discharge along a pipe from melting is quite small (<1%), and calculations with the model show that the flow time for water through a pipe 500 m long is approximately 20 min, resulting in a difference between the discharge at the upper and lower ends of <3%. The assumption of limited water input along the length of a pipe is the most debatable; however, a significant aspect of this work is that water pathways tend to flow without cross-glacier connectivity. Since water tends to arrive at the bed at discrete points, pathways only accumulate water down-glacier if they connect to another discrete input. In the case we are considering, there is (assumed) no capture, and therefore no water added to the pipe along its length. The resulting simplified equations express change in time of pipe size as

$$\frac{\partial S}{\partial t} = \frac{\sqrt{\pi S}}{L_\mathrm{H}} \frac{f_\mathrm{R} \rho_\mathrm{w} v^3}{4 \rho_\mathrm{i}} - (P_\mathrm{i} - P_\mathrm{w})^3 2 \left(\frac{1}{3B} \right)^3 S,$$

and the pressure gradient along the pipe as

$$\frac{\partial P_\mathrm{w}}{\rho_\mathrm{w} \partial s} = -\frac{\partial v}{\partial t} - v \frac{\partial v}{\partial s} - \frac{g \mathrm{d}z}{\mathrm{d}s} + \sqrt{\frac{\pi}{S}} \frac{f_\mathrm{R} v^2}{4},$$

where S is the cross-sectional area of the pipe, t is time, L_H is the latent heat of fusion for water, f_R is the Darcy–Weisbach friction factor (0.25 following Spring and Hutter, 1981), ρ_w and ρ_i are the densities of water and ice, v is the average water velocity, P_i is the ice pressure (ice thickness is 200 m), P_w is the water pressure, B is the ice viscosity parameter (5.8×10^{-7} Pa s$^{-1/3}$; Spring and Hutter, 1981), g is gravitational acceleration, z is the elevation, and s is the position along the pipe.

This reduced set of two non-linear partial differential equations allows Runge–Kutta methods to be used to calculate the pressure distribution and pipe size for each time-step instead of the more complicated finite-difference approach employed by Spring and Hutter (1981). The pressure distribution can then be found along the length of the pipe if the discharge in the pipe is given and the lower end of the pipe is at a prescribed pressure. The discharge in the pipe is equal to the water input to the moulin plus the change in water stored in the moulin. The water input to the moulin was sinusoidal to simulate the daily swing in water input from surface melt. The discharge was $(6 \pm 2) \times 10^{-4}$ m^3 s^{-1} which was about the average flow in small moulins on Bench Glacier (Reeve, 2006). Also, the pressure at the lower end of the pipe (the connection with the tunnel) was set at the equivalent of 10 m of water height.

Results and implications

The modeled diurnal fluctuations in water level are shown in Figure 12 and show that large-magnitude pressure fluctuations can be produced by a moulin–pipe–tunnel system. The channel length must be in the order of hundreds of meters to produce diurnal fluctuations of tens of meters in magnitude. The dominant control on the size of the water-level fluctuations is the length of connecting pipe, though the magnitude of the fluctuation in the discharge and the size of discharge also affect the amplitude of the fluctuations. In this case, doubling the discharge into the moulin reduces the magnitude of the fluctuations by 9%, and increasing the amplitude of the input discharge by 50% results in a 12% increase in maximum pressure. While the lengths calculated depend on the assumptions as noted, the conclusion that pipe lengths in the hundreds of meters are needed to produce the large fluctuations observed is robust.

Applying the modeling results to the borehole data from the grid area, we focus on the diurnal fluctuations in water level in the boreholes of clusters 1 and 2 (Fig. 9). A rough estimate of the pressure build-up in a pipe can be obtained by comparing the water levels of boreholes 2880-02 and 2880-04 (Fig. 7), since they are representative of the water levels for their respective clusters. The water level in the cluster with the lowest water level, cluster 2 (borehole 2880-04), can be used as an estimate of the pressure in the tunnel. The difference between the water levels of boreholes 2880-02 and 2880-04 is then the pressure build-up in the pipe which connects the boreholes of cluster 1 to the tunnel. The daily pressure build-up during the peak of diurnal fluctuations was approximately 80 m (Fig. 7). This compares to the pressure build-up produced by a 500 m pipe and indicates that the pipe connecting the boreholes of cluster 1 needed to be independent for hundreds of meters in the down-glacier direction before connecting to a tunnel. The boreholes of cluster 2 are unlikely to be recording the exact pressure fluctuations of the tunnel, but the length of the pipe connecting them to the tunnel would be shorter than that for the boreholes of cluster 1.

Our borehole measurements show a cross-glacier basal connectivity of tens of meters, while our modeling implies drainage path lengths of hundreds of meters. Combining these results suggests the basal drainage configuration of Bench Glacier differs from the progressively branching ('arborescent') channel network commonly theorized for glaciers during the late-summer season (Fountain and Walder, 1998). While the differences may appear subtle, the implications are more significant. In a moulin–pipe–tunnel configuration, the borehole water-level fluctuations do not necessarily reflect pressure variations in a tunnel, and the magnitude of the variations is not expected to decrease with distance from the tunnel. Further, a drainage configuration with limited cross-glacier connectivity and long down-glacier flow paths allows for much greater variation of pressure in a small region of the glacier bed.

Much previous research has focused on the relationship between basal water pressure (as measured by borehole water levels) and sliding (e.g. Iken and Bindschadler, 1986; Jansson, 1995) and in particular on a critical pressure above which sliding is enhanced (e.g. Jansson, 1995). A drainage system in which the lengths of the pipes control the magnitude of the diurnal borehole water-level variations may explain why sliding–velocity relationships do not always hold from one glacier to the next (i.e. Jansson, 1995) or even from year to year on a single glacier (i.e. Iken and Truffer, 1997) because the sampled pressure is determined by the configuration of the drainage system and may not represent the effective basal pressure. We stress that our analysis here applies to the late-summer period, when diurnal borehole water-level variations are prevalent, and may not necessarily hold for other times of year.

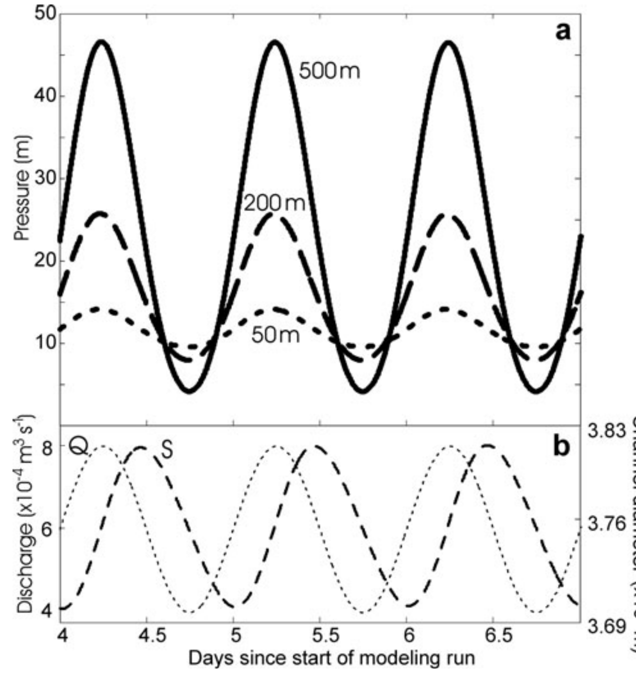

Fig. 12. (a) Modeled water-level fluctuations with different connecting pipe lengths. (b) Discharge (Q) and pipe diameter (S).

CONCLUSIONS

Diurnal fluctuations in water level were observed in the majority of boreholes on Bench Glacier when the boreholes were open to the surface (newly drilled holes) and also in a smaller percentage of the boreholes in subsequent years after they had been frozen shut by the winter cold wave. Pairs of boreholes located along the length of the ablation area often exhibited water-level variations matching in timing and magnitude. In a 16-borehole grid, a cluster analysis revealed three sets of boreholes with distinct diurnal fluctuations in water level; water levels of boreholes in the same cluster were nearly matching, while water levels in boreholes of another cluster had different magnitudes and base levels. The timing of the diurnal fluctuations was consistent between clusters. Large head gradients between clusters persisted for days to weeks and indicated that water was not flowing between boreholes of separate clusters. No uniform basal pressure was observed during the late summer.

The clusters of boreholes with distinct water-level fluctuations were inferred to be connected to a major drainage tunnel by low-discharge pipes. Observations of water levels showed the pipes had limited cross-glacier connectivity (tens of meters), and a numerical test implied that long down-glacier lengths (hundreds of meters) are necessary to produce the large-magnitude diurnal fluctuations in water level recorded in the boreholes. The implied configuration of the drainage system suggests that individual drainage pipes can run long distances down-glacier without intersecting other drainage pathways. A drainage configuration with limited cross-glacier connectivity and long down-glacier flowpaths allows for a large variation of pressure in a small region of the glacier bed and suggests that borehole water levels in late summer do not give an accurate estimate for effective basal pressure.

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