Dynamic behaviour of supraglacial lakes on cold polar glaciers: Canada Glacier, McMurdo Dry Valleys, Antarctica

The cold polar glaciers of the McMurdo Dry Valleys (MCMDV), Antarctica, are characterized by low accumulation (10 cm w.e. a^{-1}), high sublimation (7–9 cm w.e. a^{-1}) and low melt rates (1–3 cm w.e. a^{-1}) (Fountain and others, 1998). Meltwater production and flow is limited to the near surface of these cold polar glaciers, where the average ice temperature at 15 m depth is ~–17°C. Meltwater flow, as on other glacier surfaces, is confined to discrete hydrological basins, which consist of series of ice-topped pool and riffle sequences of varying dimensions (Fountain and others, 2004). The larger ice-topped pools, 10–50 m in diameter, are called 'cryolakes' (Tranter and others, 2010) and are the focus for supraglacial meltwater flow and sediment transport on Canada Glacier. They function similarly to hydrologically connected cryoconite holes (Fountain and others, 2004). We show below that water flow through this system is highly episodic during the melt season.

The supraglacial drainage system of Canada Glacier, one of the most extensively studied glaciers in the MCMDV, is ice-topped for much of the year, so that flow largely occurs below a veneer of up to 0.5 m of surface ice. The drainage system consists of a series of interconnected channels, riffles and cryoconite holes (<1 m diameter), the latter connected to the pool and riffle system by a series of linear passageways (<10 cm wide), probably the traces of former crevasses. About half the cryoconite holes are hydrologically connected, while the other half remain isolated (Fountain and others, 2008; Tranter and others, 2010). The drainage system is frozen solid throughout winter and reactivates by melting in November. Increasing solar radiation in spring melts the cryolakes internally due to a solid-state heating effect arising from the relatively low albedo of the lake ice (compared to the glacier ice) and the subsurface sediment concentrated in the lake bottom (Brandt and Warren, 1993; Podgorny and Grenfell, 1996; Fountain and others, 2008). Similar processes occur in the frozen channel beds connecting the cryolakes. The surface ice over the channels, in particular, may rot and melt out completely when air temperatures are >0°C for a few days. Melt enlargement of the channels also occurs under these same conditions. Drainage system closure due to refreezing usually begins in late January.

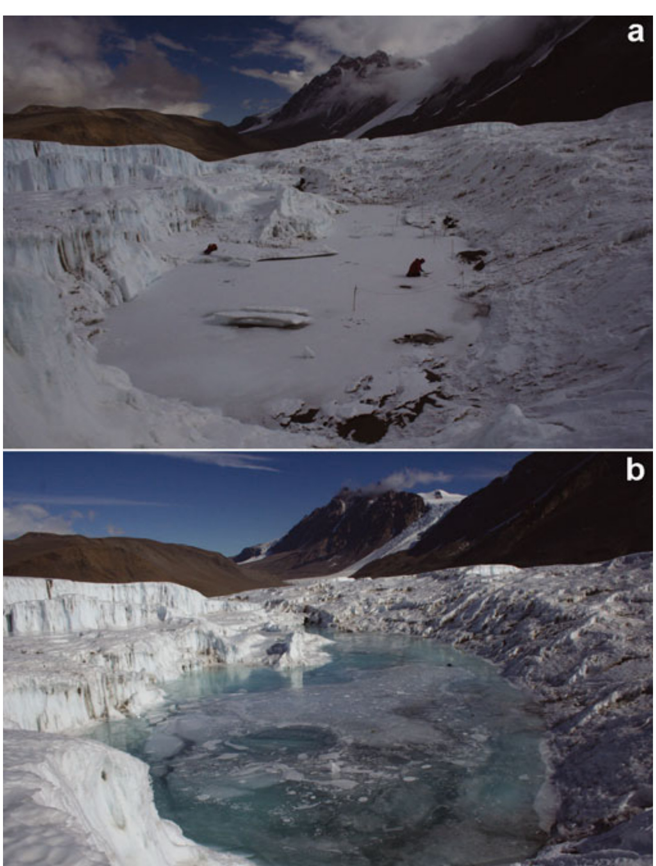

Fig. 1. A typical cryolake on the surface of Canada Glacier, Taylor Valley (77.61924° N, 162.96803° E), (a) before (7 December) and (b) after (10 December) the flood event in 2008. Note the person on the lake ice in (a) for scale; the ice lid rose by 2 m in <24 hours.

We had assumed that the cryolakes steadily melted out as the ablation season progressed (Fountain and others, 2004). Occasional observations of empty cryolake basins have been recorded, but it was presumed that the lake drainage was gradual (Johnston and others, 2005; Tranter and others, 2005). Observations in the 2008/09 ablation season show that, by contrast, episodic filling and drainage of these lakes is both possible and probably frequent. Figure 1a shows a typical cryolake on Canada Glacier on 7 December 2008. Figure 1b shows the cryolake 3 days later, after the lake rapidly flooded and the water level rose by ~2 m in <24 hours. At no point during this period did the air temperature reach 0°C (Fig. 2). The mean air temperature prior to the flood (1–6 December) was –5.7°C, with a maximum of –1.2°C. During the flood (8–10 December), the mean air temperature was –2.9°C and the maximum was –0.5°C. We infer that the increase in total diurnal solar radiation during three consecutive cloud-free days (7–9 December) was sufficient to increase production of subsurface meltwater. We further surmise that a number of upstream pools also filled during this period. Their subsequent and progressively rapid drainage, due to channel opening or downcutting, led to the rapid flooding of the cryolake under observation. Meltwater drainage from the monitored cryolake was restricted because the outflow channel was still largely frozen. We observed that smaller cryolakes higher up the same drainage basin did indeed show evidence of having filled and drained back to their former water levels during the same period. This evidence included perched ice ceilings above the cryolakes with clear void space beneath and distinctive downcut and flow-enlarged outflow channels.

We can quantify the relative fluxes of water into and out of the monitored cryolake before, during and after the flood as follows. The estimated volume of the lake increased by ~300% during the flood, from ~180 to ~630 m^3. The mean discharge during the peak summer ablation season for a number of different supraglacial streams on Canada Glacier was 2 L s^{-1} (personal communication from M. Hoffman, 2008). By contrast, the maximum discharge flowing into a similar nearby cryolake during the flood, recorded using salt tracing (Moore, 2004), was nearly a factor of 40 higher at 75 L s^{-1}. The monitored cryolake would flood in ~2.3 hours if this maximum discharge were maintained and outflow were negligible. The flooded lake would drain in 88 hours if the outlet stream flowed at the usual mean rate and no other water inputs occurred. In reality, the cryolake only drained

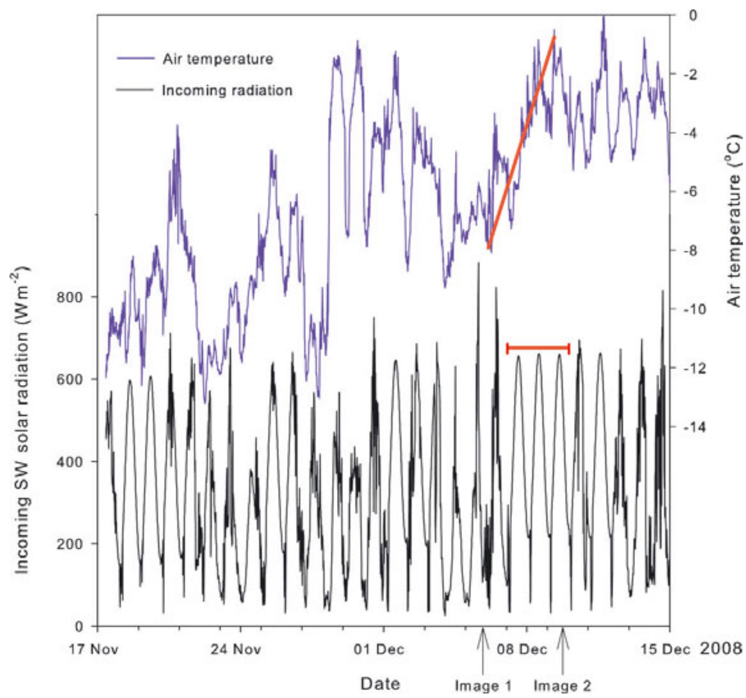

Fig. 2. Temperature and incoming solar radiation at Canada Glacier throughout the monitoring period, measured by a Campbell 107 probe and a Licor L1200X silicon pyranometer respectively. The red lines indicate the three cloud-free days which triggered the flood, and the associated increase in air temperature. The air temperature prior to the flood rose by 7°C, but did not reach 0°C.

by ~260 m^3 after 5 days, as inflows declined and outflows increased due to flow melting and enlargement of the outflow channel.

The episodic filling and emptying of cryolakes has implications for models of streamflow which are based on meteorological variables and assume a proportional response in meltwater discharge (Doran and others, 2008). Summer temperatures can be predicted with reasonable confidence using the dry adiabatic lapse rate and distance from the coast (Doran and others, 2002; Ebnet and others, 2005), and can be used to predict glacier meltwater delivery to proglacial stream, soil and lake ecosystems via simple relationships between air temperature and melt generation (Jaros, 2002; Ebnet and others, 2005). However, the temporary storage and release of meltwater during transit through the supraglacial drainage system adds a layer of complexity to this simple association. Storage of water in pools and cryolakes delays the delivery of meltwater, and hence the release can occur as a series of discrete large-volume pulses or floods to downstream ecosystems.

The role of cryolakes in the mosaic of MCMDV ecosystems in terms of water and nutrient dynamics is also likely to be more stochastic than was previously thought. The interaction of liquid water, sediment and biological material in each basin, coupled with water from the cryoconite hole network, supplies nutrient to glacially fed meltwater streams and into the ice-covered lakes (Foreman and others, 2004). Small-scale flood events, such as that described here, are more likely to send pulses of nutrient through the glacier, stream and lake ecosystems. A number of authors have proposed that the Dry Valley ecosystem operates under a 'pulse-reserve' regime (Moorhead, 2007; Wall, 2007), in which the ecosystem responds to a 'pulse' disturbance, such as an increase in the availability of liquid water, or an influx of labile nutrient from an adjacent part of the ecosystem, generating an accumulation of 'biological currency' (e.g. biota or biomass). The results of this pulse persist as a 'reserve' during normal conditions. The observed behaviour of the cryolake fits into this model well, by periodically accentuating the magnitude of the water and nutrient delivered to downstream biological communities. The longer residence time of water in the cryolakes potentially maximizes the production of organic carbon and nutrient (Bagshaw and others, 2007) before the water is released. The eventual delivery of the 'pulse' to downstream biological communities may trigger a rapid response in productivity, such as that recorded in the streams (McKnight and others, 2007) and lakes (Foreman and others, 2004).

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