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Snowmelt-Induced Slushflows, Ellesmere Island, N.W.T., Canada

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ABSTRACT

At Taconite Inlet, northern Ellesmere Island, Canada (82°50'N; 78°00'W), a snowmelt-induced slushflow marked the beginning of streamflow in 1992 from the Lake C2 watershed. Meteorological, snowpack, and hydrological measurements were made during May and June prior to the slushflow, to test a hypothesis that the most likely slushflow initiation site was beneath a large south-facing slope. Four days before the slushflow, the snowpack in flat areas was still sub-freezing (e.g. basal temperatures -9° to -11°C), with maximum snow wetness less than 1 percent (by volume). In contrast, the south slope snowpack by this time was warmer, and afternoon snow wetness was reaching 2 to 5 percent, due to higher radiative inputs. Following three days of vigorous turbulent heat transfer, a slushflow began in the stream channel below the south slope and traveled 1600 m to the lake. Discharge during the event was the highest observed during three summers (5.5 ± 2 m^3/sec), yet was insufficient to breach avalanche debris snow dams. Additional slushflows occurred elsewhere in the watershed during the following week.

INTRODUCTION

In polar regions, the transition from winter to summer occurs abruptly, due to seasonal changes in the radiation balance and large-scale atmospheric circulation. This is an important period hydrologically, including the onset of snowmelt and initiation of streamflow. In the Canadian High Arctic (north of 75°), the geographic and physiographic extent of field studies investigating these hydrologic responses to climate have been limited.

This paper presents an analysis of weather and hydrologic activity during May and June of 1992, on the mountainous north coast of Ellesmere Island, Canada (Figure 1), which culminated June 23 in a slushflow, or rapid mass movement of water saturated snow (Washburn and Goldthwait, 1958). The investigation was motivated by slushflow observations in 1990 and 1991, when without warning, slush surged in discontinuous pulses through cold dry snow filling the stream channel near camp, at 7 m above mean sea level (MSL). Insufficient time was available to investigate the origin or details of either event, although there was little indication around camp that extensive snowmelt had begun. This fieldwork was one aspect of a project to establish the paleoclimatic significance of High Arctic laminated lake sediments.

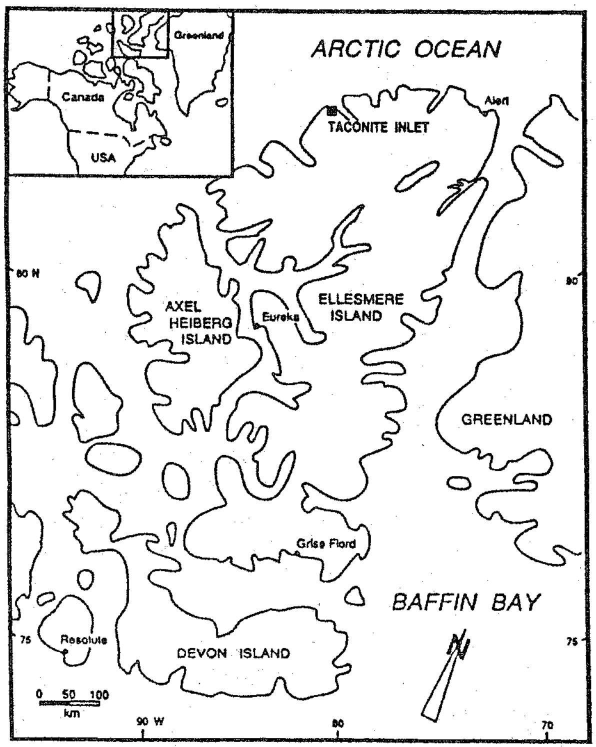

Figure 1. Location of the study area. M'Clintock Inlet is east of Taconite.

We hypothesized that the initial, channel-clearing slushflow was an annual occurrence, and originated at a site where early snowmelt was concentrated by terrain conducive to meltwater accumulation. If true, the initial slushflow would be followed by slushflow events elsewhere in the watershed, as additional source areas produced and accumulated sufficient meltwater.

PREVIOUS RESEARCH

The basic concept of the arctic-nival streamflow regime, introduced by Church (1974), has been supported by detailed investigations (e.g. Woo, 1983a). In general, the annual hydrograph is dominated by a brief early summer snowmelt peak, followed by recession to baseflow. Interannual hydrograph variability in the High Arctic is largely a product of snowmelt rate, continuity, and volume, as well as infrequent rainfall events (Church, 1988).

Lacking winter flow or an ice cover, High Arctic streams do not experience ice break-up the following year; rather, initial streamflow begins in one or more ways: as flow through or beneath the snowpack, as sheet flow at the snow surface, or as a slushflow (Woo and Sauriol, 1980). Details of the High Arctic streamflow initiation process have been well documented only for the rolling to hilly terrain typical of lowland areas (Osborn, 1852; Pissart, 1967; Woo and Sauriol, 1980; Carter *et al.*, 1987), where slushflows are not reported as the dominant mechanism of initiation.

Saturation of the snowpack prior to movement as a slushflow typically occurs when meltwater or precipitation inputs exceed outflow, as a result of permeability limitations and/or physical barriers to water drainage. Snowpack saturation decreases the cohesive strength as grain bonds are melted, and flow begins when the snowpack shear strength is exceeded. Slushflows have been observed throughout the Arctic and Subarctic in association with water courses (e.g. Washburn and Goldthwait, 1958; Rapp, 1960; Alaska Department of Highways, 1971; Nyberg, 1985), in the slush zone on glaciers (Ward and Orvig, 1953; Nobles, 1960; Müller, 1966), and in alpine regions at lower latitudes (Elder and Kattelmann, 1992).

The magnitude of documented slushflows varies greatly, from those which only displace snow from sections of stream channels (Washburn and Goldthwait, 1958) to those capable of transporting 75-ton boulders (Rapp, 1960). Slushflow frequency is also reported to be highly variable, and appears to be somewhat site-specific (Nyberg, 1985). Müller (1966) terms slush avalanching a major form of runoff, occurring on any slope of more than a few degrees (Axel Heiberg Island), while Washburn and Goldthwait (1958) state that slushflows are the characteristic method of stream breakup near Mesters Vig, Northeast Greenland. In contrast, recurrence interval estimates of very large slushflows, as determined by lichenometry or vegetation analysis, are on the order of decades (Raup, 1971) to centuries (Nyberg, 1985; André, 1990).

The observed weather conditions prior to slushflow initiation almost always indicate that a period of rapid snowmelt is required (except for those involving rainfall). Although not explicitly determined, the energy inputs have been primarily attributed to net radiation (Hestnes and Sandersen, 1987), and to positive net radiation plus energy from warm air advection (Onesti, 1985). Nyberg (1989) found initiation occurred four to five days after the daily mean temperature rose above freezing. Snowpack conditions reported in association with slushflows are highly variable, and Nyberg (1987) has suggested that snow conditions exert less control on initiation during extreme weather situations.

THE STUDY AREA

The Lake C2 watershed is situated immediately east of Taconite Inlet (82°50'N; 78°00'W), on the north coast of Ellesmere Island, Canada (Figure 1). One major stream drains 21 km^2 of the watershed, from a rugged, 9 percent glacierized basin with 1000 m of relief, underlain by continuous permafrost. The study site encompasses approximately 20 percent of the watershed, including the hypothesized areas of early snowmelt (Echo Peak south slope), initial meltwater accumulation in the stream channel, and the slushflow starting zone (Figure 2). Overall south slope gradient averages 20°, but is less uniform than it appears on the 50 x 50 m digital elevation model (DEM). The stream channel gradient is 2.5°, traversing the base of the south slope.

At the latitude of Taconite Inlet, the sun is continuously above the horizon after early April, and reaches solar altitudes on the summer solstice of 31° and 16°, at noon and midnight local apparent time (LAT). Mean monthly air temperature at nearby weather station Alert (Figure 1) increases from -11.6°C in May to -0.8°C in June.

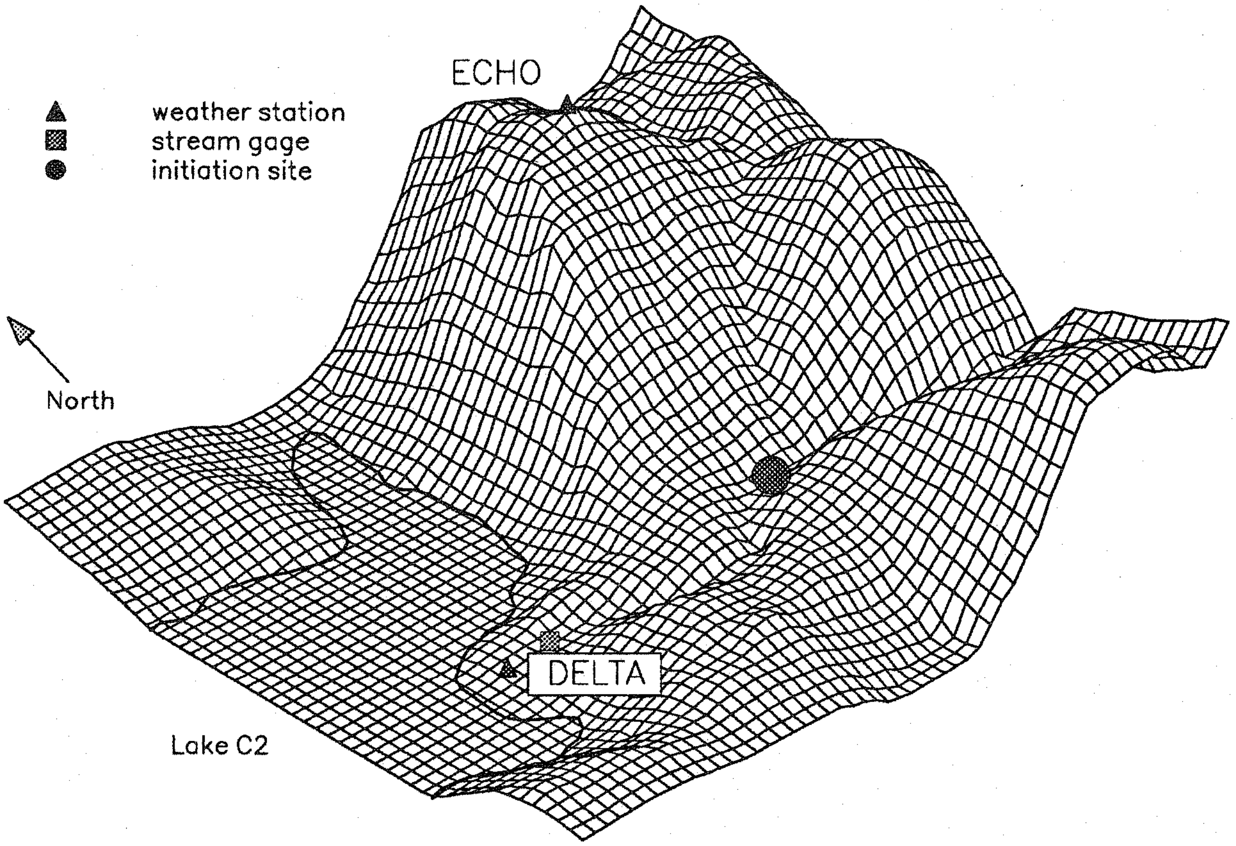

Figure 2. The western portion of the Lake C2 watershed, viewed from 31° above the horizon, and from an azimuth of 225° true. Grid spacing is 50 X 50 m; vertical exaggeration is X 2. Delta and Echo weather stations were at 7 m and 518 m above MSL.

FIELD METHODS

Automatic weather stations (AWS) were operated on the Lake C2 delta and on top of Echo Peak (Figure 2), at 7 and 518 m above MSL, to measure the timing and magnitude of atmospheric energy inputs to the snowpack (hereafter Delta and Echo sites). Data were collected with nearly identical sensors, beginning May 17 on the delta, and May 21 on Echo Peak. Incoming thermal radiation was calculated using pyrgeometer thermopile output, case temperature and a correction for short-wave interference (Wardle and McArthur, 1992).

Internal snowpack temperatures were measured within 50 m of each weather station by vertical thermocouple profiles (10 cm spacing). At irregular intervals, the snowpack adjacent to each station was characterized by measurement of stratigraphy, grain size and type, temperature (calibrated dial-stem thermometers), density (200 cc Taylor-LaChapelle cutter and Ohaus electronic balance), and snow wetness (Denoth dielectric sensor). Snowpack measurements on the south slope were primarily made between 150 and 250 m above MSL, and at the base of the slope (Figure 2).

A stream gaging station was established on the delta (Figure 2) at a stable cross-section. Discharge was measured two to four times daily early in the season by the conventional current-meter method (Rantz and others, 1985), using a Swoffer model 2100 current meter. Stage height was measured with a Stevens Type F Water Level Recorder, installed 50 hours after the initial slushflow, allowing stage-discharge relations to be established.

RESULTS AND DISCUSSION

Weather

The energy available for snowmelt is governed primarily by incoming radiation, air temperature, and wind velocity. These variables, measured at the Delta site, are plotted on Figure 3. Echo Peak values are comparable, although were 0.7°C warmer during June, and slightly windier.

Total incoming radiation is the sum of incoming solar and thermal radiation. This parameter was selected to illustrate the radiative flux because, unlike net all-wave radiation, it is less governed by site specific factors. For example, the albedo beneath the delta radiometers dropped from 0.9 to 0.2 within 48 hours, as the site became snow free (1700 h June 19 to 1700 h June 21). Consequently, net all-wave radiation over the same period went from -13 to 213 W/m^2, and was no longer representative of the snow covered study area.

Through the study period, total incoming irradiance exhibited primarily a diurnal signal, with a slightly increasing trend through late May (Figure 3a). The lowest values of mean daily solar irradiance were recorded June 19 and 22, due to cloud cover. Radiative inputs were therefore relatively low immediately prior to the slushflow on June 23.

On June 19 (Julian Day = JD 171), the air temperature rose above freezing (Figure 3b), and the mean on June 20 was 6.8°C. The highest daily mean prior to this was 0.2°C on June 10. Accompanying the warmer temperatures were higher wind velocities (Figure 3c), which were steadily from an azimuth of 170-240° true (S to SW) during the warmest period.

Figures 3b and c indicate that substantial advection of warm air began abruptly, and continued from June 19 to 21. As a result, considerable energy was available for turbulent heat transfer to the snowpack, during a time of decreased radiant energy flux (Figure 3a). This regional advection event terminated a period of gradual warming and ripening of the snowpack.

Snowpack evolution

The snowpack late in May was cold and dry, largely comprised of low density, faceted grains (Figure 4a). Snow depth, measured on June 4 along a transect up the south slope, averaged 63 cm (n = 98), and was highly variable (coefficient of variation = 2.17). Mean snowpit temperatures near the AWS sites on May 20 and 21 were -16°C at Delta, and -13°C at Echo.

The most significant snowpack variables relating to slushflow initiation were temperature and wetness. Snow temperature was important because, until the snowpack became largely isothermal at 0°C, most of the meltwater produced at the surface refroze within the snowpack, and was not available for runoff. Wetness measurements provided an indication of meltwater production and storage in the snowpack. Based on temperature and wetness data, the study interval was divided into two periods: before and after June 20 (JD 172).

Prior to June 20, snowpack temperatures at both sites document gradual warming (Figure 3d and e). After one month, mean snowpack temperatures had increased to -7°C, while snow wetness remained unmeasurable in both Delta and Echo snow. Gradual warming of the snowpack at these horizontal sites through June 20 parallels the gradual increase in total incoming radiation. Meanwhile, on the south slope, radiative inputs were warming and ripening the snowpack faster than the other sites. This was demonstrated particularly on three nearly clear days (June 8, 14 and 16), where at noon on the 20° slope, the geometrically calculated direct-beam solar irradiance was 152 percent greater than that on horizontal surfaces. As a result, the wettest south slope snow on June 8 was 2 percent by volume at 1 cm depth, 3.5 percent on June 14 at 8 cm, 3 percent at 1 cm on June 16, and 4.9 percent in the wettest snow (at 6 cm) on June 17.

The snowpit profile made at 1500 h June 16 (Figure 4b) was typical of the warming south slope snowpack, where meltwater percolation had begun. Applications of a dye tracer, and extensive excavations, indicated meltwater was moving downslope parallel to the surface at about 1 m/hr, primarily as conduits in the upper 5-10 cm of the snowpack. Isolated areas were also observed where meltwater had percolated to the base and refrozen.

On June 20 (JD 172), dramatic snowpack changes at all sites accompanied the warm air advection, detailed above. The most notable of these was very rapid warming of the entire snowpack (Figure 3d and e). To illustrate, several thermocouples in cold snow (e.g. -10°C) recorded brief 0°C spikes prior to warming, apparently indicating the arrival and freezing of meltwater. A Delta snowpit on June 21 was isothermal at 0°C and documents that the snowpack had become significantly wetter (Figure 4c).

Early meltwater runoff

Despite the increase in snow wetness on June 20, no areas of free water collection, or full saturation, were found. Observations between 2000 and 2200 h, on the south slope and at the stream channel, found basal snow to still be predominantly cold and dry. Early on June 21, at the base of the south slope (Figure 2), the first ponding of

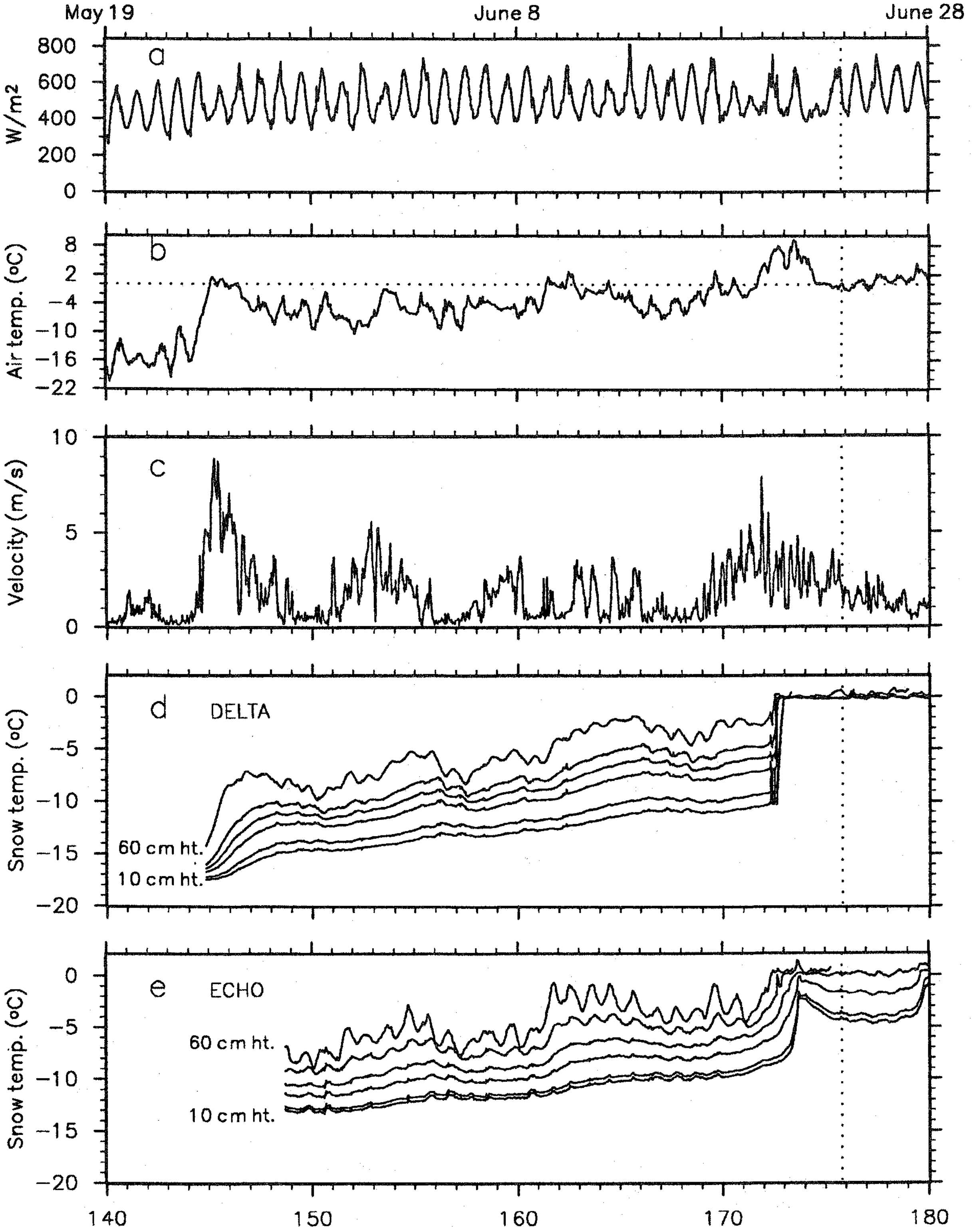

Figure 3. Weather and snow temperature data measured during the period May 19 (JD 140) to June 28 (JD 180) 1992: Major tick marks begin each day. (a-c) Delta hourly mean total irradiance; air temperature; and wind velocity; (d) Delta snow temperatures (30 minute means) at heights 10 cm to 60 cm; and (e) Echo snow temperatures (30 minute means) at heights 10 cm to 60 cm. Vertical dotted line indicates time of slushflow.

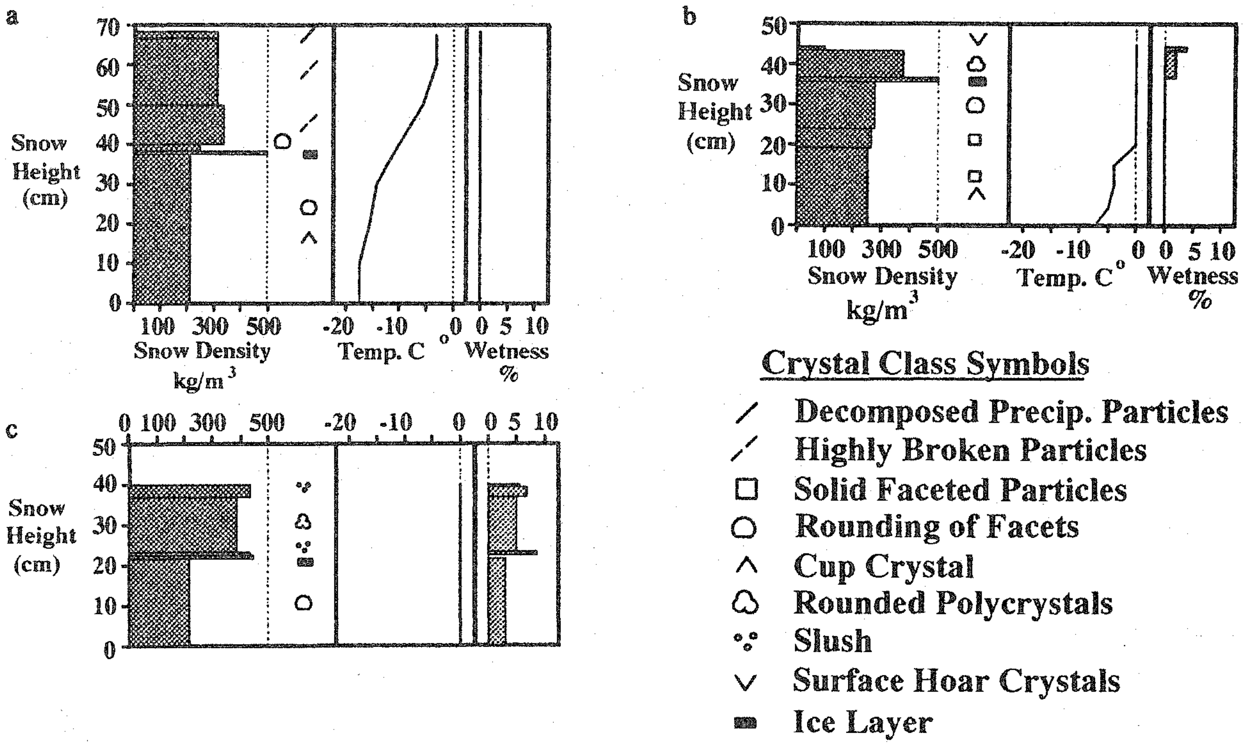

Figure 4. 1992 snowpit profiles: (a) the Delta profile of May 26 (JD 147) was typical of the early season snowpack; (b) the south slope snowpack had warmed considerably by June 16 (JD 168), but remained cold and dry at the base; and (c) by 1700 June 21 (JD 173), the delta snowpack had become isothermal at 0°, and much wetter. Crystal class symbols (ICSI, 1989) are in stratigraphic position.

meltwater was located, saturating the 75 cm deep stream channel snowpack to a depth of 10-15 cm. At 1400 h, meltwater drainage estimated at <0.001 m^3/s was observed beneath the snowpack in a tributary channel immediately upstream and north of the initial ponding site. By 2000 h on June 21, several discontinuous sections of stream channel snowpack, above and below the initial ponding site, had become saturated to the surface. These ponded areas were 2-3 m wide, and the wetting front was slowly extending downstream.

Unsaturated areas of stream channel had become the exception by 0600 h on June 22, between the tributary described above and a snow avalanche deposit approximately 1000 m downstream. Discharge through and at the snow surface was estimated at 0.005 m^3/s, and had begun to fill the area behind the avalanche deposit. This snow avalanche dam (approximately 4 m high) was the largest of several between the south slope base and the lake; further upstream several snow avalanche deposits 4-6 m high had not begun to fill with meltwater. Ponding continued behind the lowest avalanche dam for two hours, before spilling over the threshold as surface flow. Stream channel snow saturation and surface flow reached the lake approximately at midnight.

The streamflow initiation events thus far differed from those of 1990 and 1991, when slushflows were the first indication at sea level of any runoff. In 1992, pre-slushflow discharge on the afternoon of June 22 was 0.035 m^3/s, and dropped to 0.022 m^3/sec at 1000 h on June 23 (Figure 5). Overnight temperature minima were -0.8° and -3.4°C at the Delta and Echo sites. Meanwhile, despite low discharge at the stream gage, a considerable volume of meltwater had been retained by avalanche dams, and by a ribbon of saturated snow wider than the stream channel itself. The effect of this water through time was to reduce the shear strength of the saturated snow.

Slushflow

On June 23 at 1850 h, a slushflow was initiated in the stream channel, beneath the south-facing slope (Figure 2). The slushflow traveled at approximately 1 m/sec, pushed aside most of the snow from 1600 m of channel, and initiated 1992 channelized streamflow. The total volume of discharge during the slushflow was indirectly

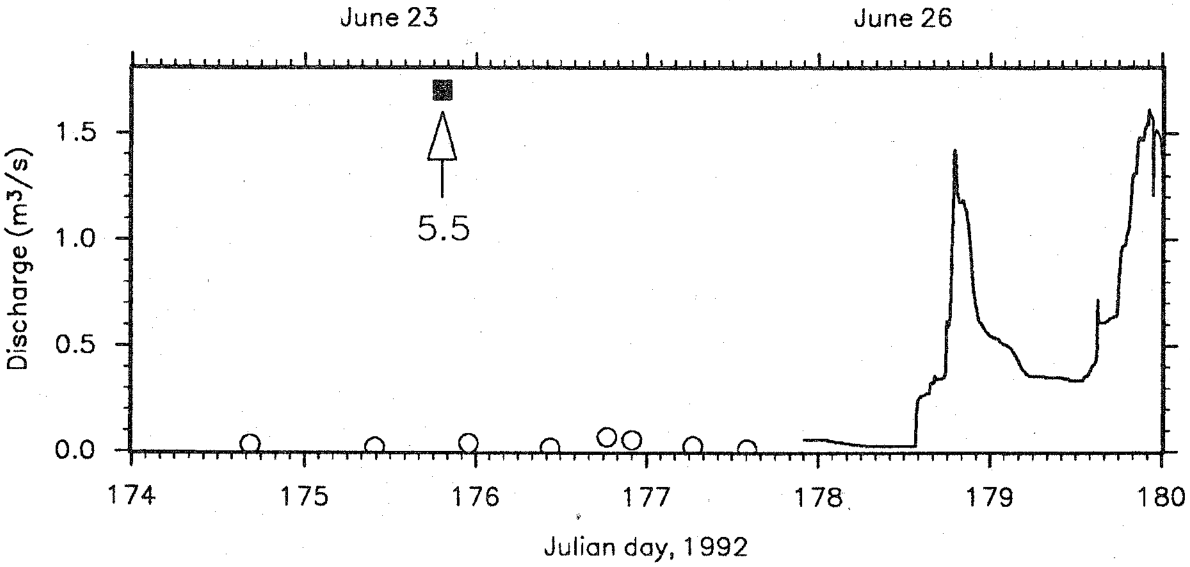

Figure 5. Streamflow on the Lake C2 delta through June 27, 1992. Major tick marks begin each day. Circles are actual current-metered discharge measurements during the initial four days of streamflow. Note that the estimated slushflow discharge is off-scale, at 5.5 m^3/s. The hydrograph beginning June 26 (JD 178) is derived from stage values at a 15 minute interval.

calculated using high water marks at 5.5 ± 2 m^3/s (Figure 5). This was the greatest discharge from the watershed during three field seasons, 1990-92.

From an observation point at 250 m above MSL on the south slope, there was no apparent trigger of the slushflow. Later inspection of the initiation site suggested the following sequence of events: a sheet flow of water (and slush?) at the snow surface came through a slight constriction in the channel, causing collapse of the saturated snowpack and release of the slushflow.

The snow avalanche dams were saturated and impounding meltwater when the slushflow passed by, yet were not breached. Although sudden release could occur under different circumstances, avalanche dams in mountainous terrain may attenuate discharge peaks, in contrast to the accentuating effect of snow dam failure reported from elsewhere in the High Arctic (cf. Woo, 1983b).

Subsequent events

Several lines of evidence indicate that additional slushflows followed the initial event. At the stream gage, discharge on June 24 and 25 remained below 0.08 m^3/s until 1340 h on June 26, when an increase occurred rapidly enough to be audible (Figure 5). The rise in discharge was associated with increased concentrations of slush and suspended sediments. Several additional pulses of slush and suspended sediment occurred during the afternoon, until just before 1900 h.

At 1500 h on June 27, discharge at the gage almost doubled within a few minutes (Figure 5), accompanied by slush and suspended sediment concentrations even higher than the previous day, along with abundant plant fragments. This event probably resulted from a slushflow on the south slope, in a poorly defined watercourse, which also transported small boulders (up to 30 cm long axis). This particular slushflow had not occurred at noon, when snowmelt runoff was actively taking place on the south slope, yet the path was evident early June 29, on the next south slope observation. Less dramatic pulses continued at the stream gage on June 27 until 2300 h, and recurred daily into July.

The slushflow activity on June 26 and 27 was associated with rapid snowmelt, particularly at higher elevations. June 24 through 28 (JD 176-180) was a time of low incoming thermal radiation, but nearly clear skies through the period resulted in maximal solar radiation. During this period, the highest daily incoming radiation totals of the entire summer were recorded, which was further intensified on the south-facing aspect. Although Delta air temperatures ranged between -1° and 2°C through the period (Figure 3b), temperatures at Echo became positive on June 26 (JD 178) and remained between 5° and 7°C for 36 hours. This was the first prolonged inversion of the 1992 field season, and combined with radiative inputs, the effect on snow temperatures at 500m was dramatic (Figure 3e). Whereas Echo snowpack temperatures had dropped from June 21 to the 26th, the entire snowpack reached 0°C by early on June 28 (JD 180).

Slushflow activity following the initial event occurred as additional source areas experienced snowmelt and snowpack saturation. Unlike the cloudy and turbulent weather preceeding the initial event, these slushflows were associated with high radiative energy inputs, and a strong temperature inversion, resulting from regional atmospheric stability.

CONCLUSIONS

Hydrologic activity in the Lake C2 watershed began in 1992 following rapid warming of the snowpack, increased meltwater production, and ponding of meltwater beneath a large south slope. A valley-bottom slushflow then initiated channelized streamflow, as in 1990 and 1991, and was followed by additional slushflows elsewhere in the watershed. This sequence of events suggests that slushflows are annual events, originating from partial source areas, in regions of the High Arctic with high topographic relief.

The apparent frequency, and relatively high discharge magnitude, of slushflows in this area has implications for future hydrologic research. In particular, these findings indicate that discharge and related parameters such as water temperature, electrical conductivity and sediment load must be monitored and sampled at a high frequency, to adequately resolve their early season variability.

The abrupt snowpack changes observed, associated with advection of a warm air mass, demonstrates the sensitivity of hydrologic processes at the highest northern latitudes to large-scale atmospheric circulation. Further analysis of the 1992 data will include energy balance partitioning, and investigation of persistent negative 500 mb height anomolies during the period (cf. Halpert and Ropelewski, 1993), in an effort to better understand how High Arctic hydrologic processes respond to climatic variability.

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