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Impact of High-Latitude Chinook Events on Arctic Glacier Hydrology

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ABSTRACT

This paper describes the effect of a chinook event that occurred on 28–30 July, 2000, on the hydrology of a polythermal Arctic glacier. First, we describe the synoptic conditions that produced the chinook, and the local meteorological conditions associated with it. We then determine the amount and proportion of summer melt generated by the event using both energy balance and degree-day methods, and assess its impact on glacier hydrology. Finally, we examine a 50-year synoptic record of Arctic climate to determine how often similar events may have occurred in the past.

Keywords: glacier hydrology, synoptic climatology, energy balance, degree-day, ablation, hydrometeorology, Arctic

INTRODUCTION

A chinook event can be caused by several mechanisms. The most common is when a pressure gradient forces a stable air mass over a topographic obstacle, such as a mountain range. The air mass warms at the dry adiabatic lapse rate as it descends on the lee side of the mountains, increasing local air temperatures by up to 10ºC, causing strong warm winds perpendicular to the mountain range, and leading to an abrupt decrease in relative humidity (Barry, 1992).

Chinooks are significant for local meteorology due to their three main effects: increased air temperature, decreased relative humidity, and increased wind speeds. These are especially significant in glaciated environments, where melt is driven by temperature and vapour pressure gradients between the glacier surface and the overlying air (Brazel et. al., 1992). Thus the effect of a chinook on a glaciated basin can be quite significant, leading to enhanced melt and increased runoff production. Chinook effects may be especially significant in areas such as the High Arctic, where total summer melt is very low to begin with.

STUDY SITE

John Evans Glacier is a valley glacier located at 79° 40′ N, 74° 00′ W on eastern Ellesmere Island, Nunavut, Canada (Fig. 1). It covers approximately 75% of a 220 km^2 catchment, with a length of 15 km and an elevation range of 100 - 1500 m a.s.l. (Skidmore, 1995). Ice thicknesses reach a maximum of ~400 m close to the equilibrium line, and 100-200 m in the lower 4 km of the glacier. The glacier is polythermal, with cold-based ice in the accumulation area and at the glacier margins where ice is thin, and warm-based ice throughout the remainder of the ablation zone (Copland & Sharp, in press).

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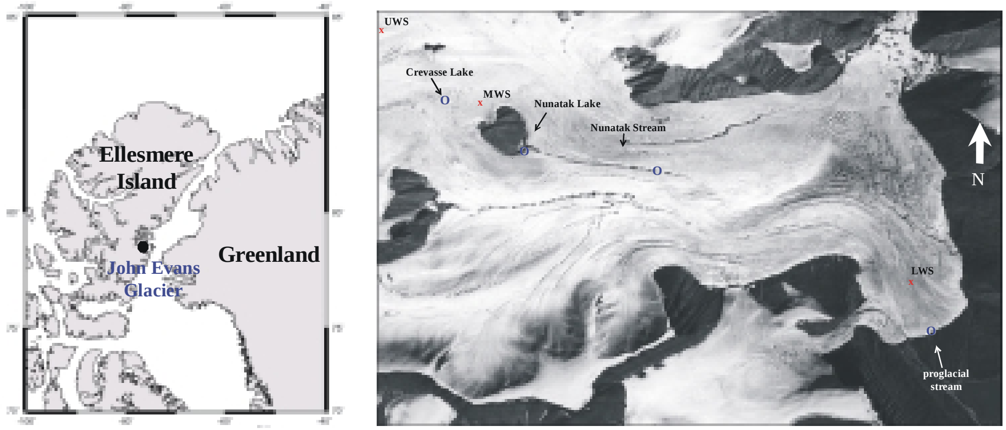

Figure. 1. Study site location and aerial photograph.

At the beginning of the melt season, the drainage system consists of disconnected supraglacial lakes and streams, with no proglacial outflow. As surface melt advances, snowmelt is routed into storage in ice-marginal lakes which remain isolated from the remainder of the drainage system (e.g. Nunatak Lake; Fig. 1). Snowmelt is also routed into supraglacial channels, which are composed of discrete ponds that progressively interconnect via englacial channels as the melt season progresses (e.g. Nunatak Stream; Fig. 1). Eventually, the final pond in each stream system becomes connected to a moulin approximately 4 km from the glacier terminus, allowing water to drain to the glacier bed. Proglacial outflow of subglacially routed waters is initiated within 24 hours of this connection.

Meteorological data have been collected at JEG since May 1996 at three on-ice stations, located along the glacier centreline at 1183 m a.s.l. (UWS), 824 m a.s.l. (MWS) and 261 m a.s.l. (LWS), respectively (Fig. 1). This study focuses on the meteorological record from the UWS, as it is above the long-term equilibrium line altitude (ELA) of the glacier, and should therefore show the effects of the chinook most clearly.

METHODS & RESULTS

Synoptic conditions

Synoptic conditions for 28-30 July, 2000, were analysed using the National Centre for Environmental Prediction's (NCEP) CDAS daily reanalysis datasets (Kalnay et. al., 1996). Conditions were also compared with a 50-year record of synoptic 'types' (Keimig, unpub. data) to examine the possible recurrence interval of synoptic conditions similar to those associated with the chinook event.

500mb maps indicate a low over northwestern Greenland which deepened and moved into Baffin Bay, a stationary low over the Barents Sea, a weak high over the Arctic Ocean, and a high moving northwards from the Queen Elisabeth Islands (Fig. 2). This high reached its most northerly position on JD 211, working with the low over Greenland to route airflow westwards over the northern sections of the Greenland ice sheet, where it merged with flow entering the area from the Arctic Ocean. This resulted in strong easterly winds over the east coast of Ellesmere Island. This synoptic situation developed over JD 210 (28 July) and 211 (29 July), and was at its peak on JD 211. By the end of JD 212 (30 July), the high had disappeared, and the low over Greenland had moved south-westwards, over Baffin Island.

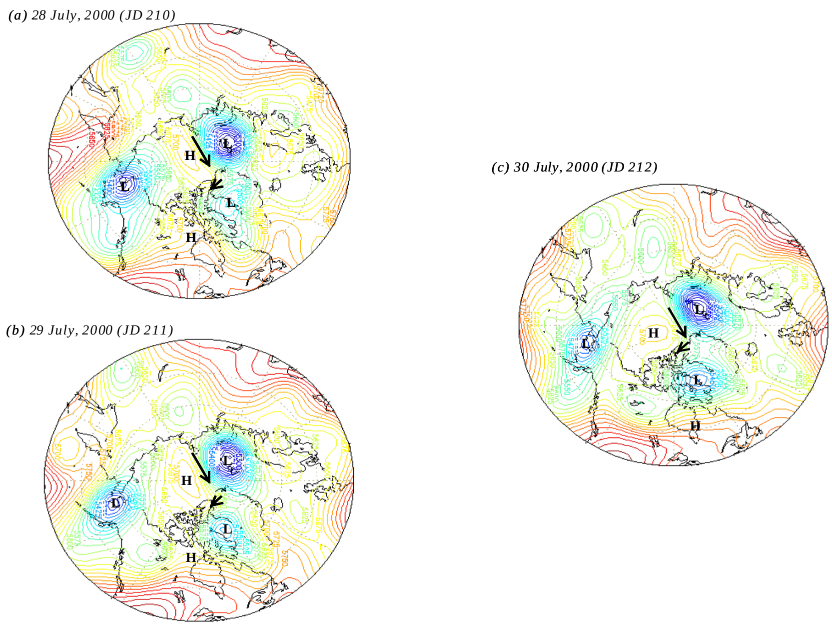

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Figure 2. 500mb synoptic conditions during the chinook event.

A search of the synoptic classification done by Keimig (unpub. data) suggests that synoptic conditions similar to these occurred on 2.3% of days in the period 1948-1999.

Local meteorology

The start of the chinook was marked by a shift in wind direction to NE on JD 210 (Fig. 3). This shift mirrors the wind direction observed on the synoptic maps, and was accompanied by an increase in both wind speed and air temperature, and by an initial drop in RH. By late JD 210, however, RH had returned to normal. Wind speeds reached hourly maximums of 11 m/s, while temperatures reached hourly maximums of 8°C. By JD 213 the air temperature had returned to background values. Winds at the UWS did not shift back to W-NW until JD 214.5.

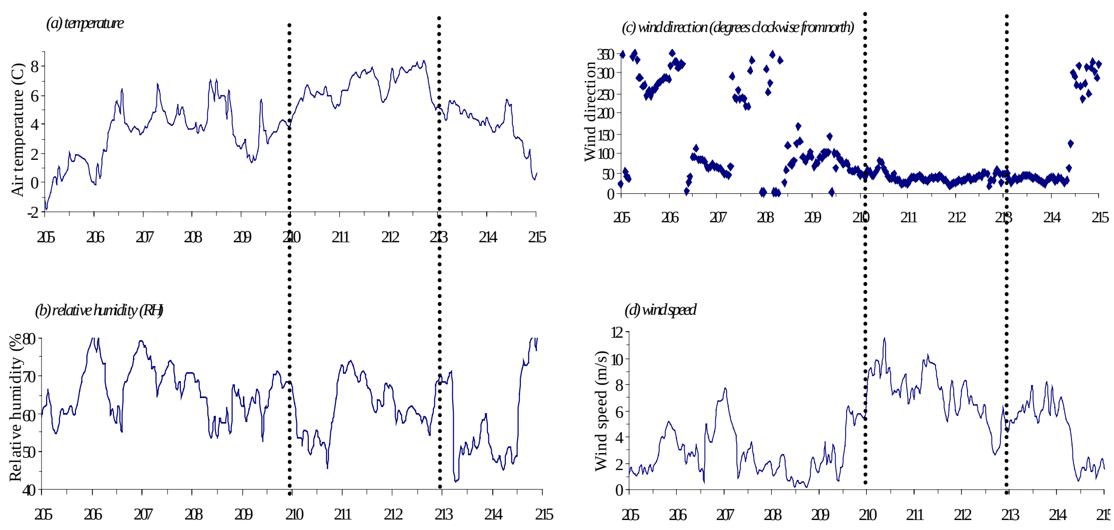


Figure 3. Local meteorological conditions at the upper weather station.

Examination of the five-year record from JEG indicates that similar conditions have not occurred during that time period. A slightly similar event was recorded in the meteorological record on 10-11 August, 1999, but occurred only at the MWS, and did not reach the same magnitude as the 2000 event.

Melt calculations: Energy balance

Surface melt rates were calculated using an energy balance model (EBM) developed by Brock & Arnold (2000). The model requires as input the latitude and longitude, slope, aspect, elevation, albedo, and roughness of a given point on the glacier, as well as the meteorological station elevation. For a more detailed description, see Brock & Arnold (2000).

Melt was calculated using data from 9 June – 3 August, 2000 as model inputs. The meteorological record from the UWS was divided into six subsections based on measured albedo values, and each subsection was assigned an aerodynamic roughness length from Paterson (1994). Separate model runs were performed for each sub-period. Total seasonal melt was calculated by summing the daily totals. The proportion of the summer melt that occurred during the chinook was determined by dividing the melt sum from 28-30 July by the seasonal total.

EBM calculations indicate that melt produced at UWS during the chinook (JD 210-212) constituted 27% of total seasonal melt, while the chinook itself occupied only 5% of the melt season (Fig. 4). The proportion of melt contributed to total seasonal runoff during the chinook was approximately 67% at UWS, based on the assumption that the first 60% of melt goes to internal accumulation processes and superimposed ice formation (Reeh, 1989).

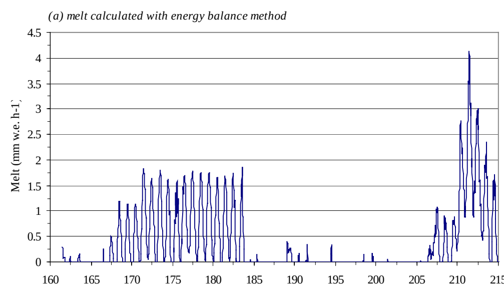
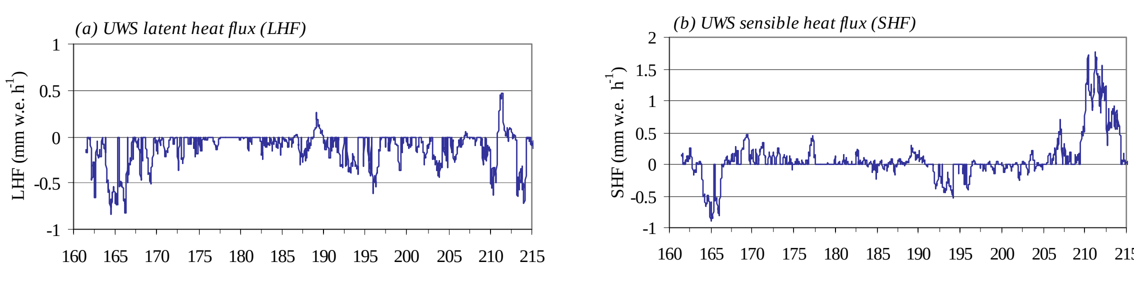


Figure 4. Melt calculated with energy balance method.

The relative contributions of each energy balance component changed significantly over the season (Fig. 5), with SHF and LHF contributing very positively to melt during the chinook event. This is in contrast to their melt contributions during the remainder of the season, when LHF is generally negative and SHF is very low. Q*, however, shows no greater contribution to melt during the chinook than earlier in the season. This suggests that, during the chinook, it is the turbulent fluxes which are instrumental in enhancing melt.



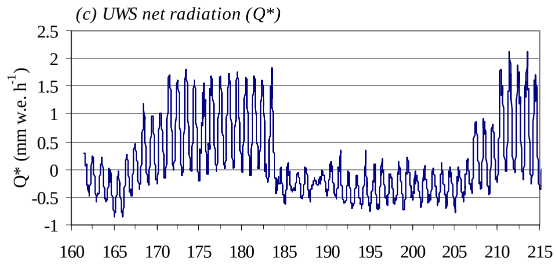


Figure 5. Contribution of each energy balance component to melt.

Melt calculations: Degree-day

Melt was also calculated with a degree-day method, using a degree-day factor determined by previous researchers at the site (Arendt, 1999). This allowed us to examine how calculated melt amounts differ in areas where chinooks occur when using a method that uses only air temperature fluctuations.

Examination of predicted melt rates over the season reveals that, although melt rates calculated with the DD method follow a similar trend to those calculated with the EBM, melt during the chinook event is underestimated by 50% with the DD approach (Fig. 6). The majority of studies use the DD method due to a lack of input data for an EBM (Braithwaite, 1984), and therefore utilise standard DDFs derived for given glacierised surfaces: 3-5 mm w.e. d^{-1} $°C^{-1}$ for snow, and 5.0-14.0 mm w.e. d^{-1} $°C^{-1}$ for ice (Braithwaite, 1995). While use of these standard values will almost certainly neglect the effects of chinook events on melt due to their inability to incorporate the effects of turbulent heat fluxes on melt, calculation of more precise DDFs from energy balance model output would require much more data, thus rendering the DD method redundant.

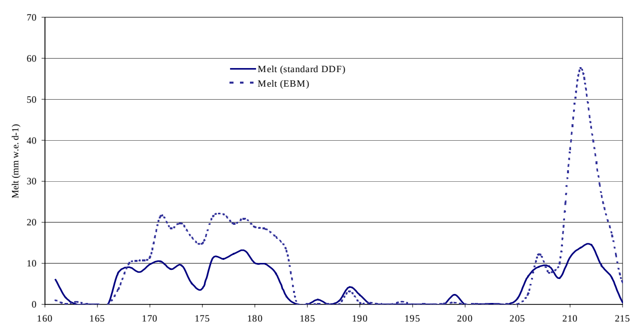


Figure 6. Melt calculated using EBM versus degree-day method.

Glacier hydrology

Keller 169-L pressure transducers connected to Campbell Scientific CR10 dataloggers were placed in the Nunatak Lake, Nunatak Stream, and Crevasse Lake (Fig. 1), to record fluctuations in water level due to ablation inputs. Relative stage values were recorded every 10 seconds, and an average reading was output every 15 minutes. Physical observations of drainage system development over the melt season, including estimates of discharge volumes, were also used to determine the impact of the chinook on glacier hydrology.

Due to extensive channel aggradation and migration, the record from a transducer placed in the proglacial stream was unreliable. However, electrical conductivity (EC) readings were taken every 10 seconds and the average was recorded every 10 minutes, using a Campbell Scientific CS547 conductivity and temperature probe connected to a Campbell Scientific CR10X datalogger. These readings provide an indication of changes in the mean subglacial residence time of waters draining from the glacier. When the EC probe was buried by stream aggradation, samples were collected at one-hour intervals using an American SIGMA pump sampler; these samples were measured every 24 hours using a hand-held Cole Palmer EC meter. When the sampler was destabilised due to high water levels, manual readings of proglacial EC were taken once a day with the Cole Palmer EC meter until the sampler could be reinstalled.

Transducer records from the supraglacial system indicate that all water bodies experienced the second-highest flows of the season during the chinook event (Fig. 7). Stage values were higher only at the beginning of the season, when water ponded in separate portions of the drainage system before interconnection occurred.

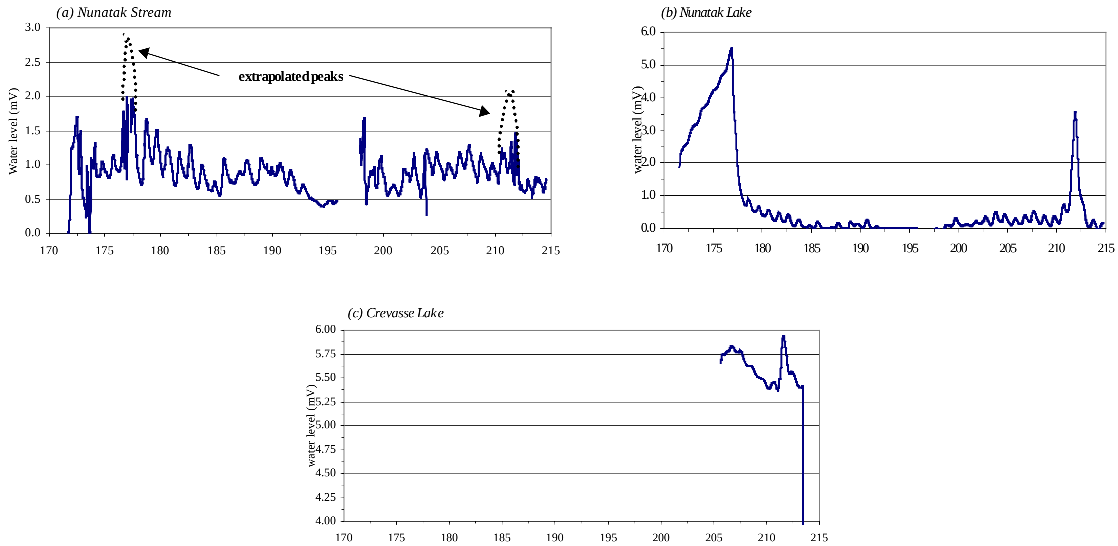


Figure 7. Stage records from the (a) Nunatak Stream, (b) Nunatak Lake and (c) Crevasse Lake. Note that, due to observed sensor movement during high flows, Stream peaks were extrapolated.

Water levels began to rise on JD 210, peaking at 16.00h (Nunatak Stream and Crevasse Lake) and 21.30h (Nunatak Lake) on JD 211. Physical observations of the drainage system during the chinook indicated extremely high melt rates and discharge volumes. Discharge in supraglacial streams began to increase early on JD210, while the surface layer of the glacier, in which cryoconite holes had developed, was removed. In addition, proglacial discharge remained extremely high until 23.00h on JD 210 (Nienow, pers. comm.).

Two large moulins were also observed to develop on the upper glacier, upstream from the Nunatak (Fig. 1), perhaps impacting subglacial drainage. Rapid drainage of the Crevasse Lake on JD 213 at 11.00h was also recorded, and may have had a similar effect on subglacial hydrology as the opening of the moulins.

Proglacial EC shows a broad peak on JD 211, after which EC values dropped below seasonal average values. Observations in the proglacial area indicate that the conduit from which subglacial waters emerged had widened from 2 m to approximately 10 m, and that massive amounts of water were exiting the glacier and covering a greater area of the proglacial outwash plain than earlier in the season. This was coincident with the high melt rates at the surface. The peak in proglacial EC occurred in tandem with a peak in suspended sediment concentrations (SSC), indicating that in-channel weathering of suspended sediments was very high during the event.

DISCUSSION

Synoptic, meteorological and energy balance conditions

The synoptic conditions over 28-30 July, 2000, created a large-scale pressure gradient between the low over NW Greenland and the high over the Arctic Ocean, forcing air to rise orographically over the north-eastern portion of the Greenland Ice Sheet. The descent of this air on the lee (NW) side of the ice sheet led to adiabatic warming, and northeast winds fed warm air into the study area at high speeds, under clear, cloudless skies.

While the clear skies during the chinook maximised net radiative flux at the glacier surface, the melt response was more significantly enhanced by turbulent fluxes. Melt model results indicate that melt rates during the chinook initially increased mainly in response to increased sensible heat transfers, while latent heat energy was directed out of the glacier surface by significant evaporation. However, the equilibration of the melting surface with the overlying atmosphere allowed melt rates to peak on JD211, as high temperatures and high winds worked in tandem to increase LHF and SHF and enhance melt response.

Shortcomings of the DD method

Obviously, use of constant degree day factors allows for a potential underestimation of melt in years when a chinook occurs, because of a failure to take into account the wind speed enhancement of melt. This is especially important given the short Arctic melt season, during which chinook events can account for a large percentage of seasonal melt. Running the DD model with these standard values for melt results in up to a 50% underestimation of total seasonal melt at the UWS, with melt during the chinook underestimated by 71%. This may be significant for glacier mass balance depending on how often chinooks recur; for example, a 50% underestimate of melt is significant in the context of a single year, but is much less significant if chinooks recur only once every 50 years. Frequent occurrence, however, may have a negative effect on summer mass balance that is disproportionate to event duration (Alt, 1978).

The main problem with the degree-day method is that DDFs are fixed in space and time (for each surface type), and thus do not incorporate subtle variations in both surface and atmospheric conditions that could affect melt calculations. The data required to incorporate these influences into degree day modelling are sufficient to allow energy balance modelling, which is preferable to the degree day approach where data allow it.

Effects on hydrology

As the chinook event was instrumental in increasing melt and meltwater inputs to the glacier drainage system, it had a significant impact on glacier hydrology. The peak in the supraglacial stage record suggests inefficient routing of water through the drainage system, indicating either the presence of blockages within the englacial channels that connect the supraglacial ponds, or that melt inputs exceeded transport capacity, thus increasing intermediate storage. The period before the chinook was characterised by cold, overcast conditions, and the surface of many ponds in the Nunatak Stream system was observed to be perpetually frozen. This would create ideal conditions for blockages to form both through refreezing of meltwater in englacial channels (Hodgkins, 1997), and through blockage of these channels by mobilisation of the ice cover of the streams. At the onset of the chinook event, therefore, the reduced capacity of the drainage system was unable to accommodate the sudden influx of meltwater, thus causing the system to 'back up' and create a peak in supraglacial water levels. Once high flows had continued long enough to clear these blockages and widen drainage channels, the system was able to accommodate the increased meltwater inputs. Thus stage dropped to lower than pre-event levels, despite continued high melt rates, due to the increased drainage system efficiency and subsequent reduction in meltwater transit times.

There is also the suggestion that the chinook event contributed to the expansion of subglacial drainage. The opening of moulins in the upper parts of the glacier (Nienow, pers. comm.), routed water that had previously drained supraglacially directly to the glacier bed. This indicates either that the enhanced surface meltwater inputs increased the kinetic energy of the stream sufficiently to penetrate the cold ice without refreezing (Hodgkins, 1997), or that snow blockages were removed from the crevasses, allowing them to fill with water, propagate to the bed, and drain as moulins (Weertman, 1973; Scambos et. al., 2000). Regardless of the method of formation, these moulins presumably allowed supraglacial channels farther upglacier to connect with subglacial channels, thus expanding the subglacial drainage system and allowing it to drain a larger proportion of the glacier (Nienow et. al., 1998). The enhanced meltwater input would increase drainage system efficiency, allowing large volumes of surface meltwater to flush the bed and exit the glacier snout.

The observation of large volumes of water exiting the glacier snout, in combination with the sudden decline in proglacial EC immediately following the chinook, supports this hypothesis. During the chinook, expanded subglacial drainage due to opening of up-glacier moulins allowed high supraglacial inputs to flush sediment from large areas of the bed. The peak in proglacial EC indicates extensive contact of low-EC surface waters with high sediment concentrations at the bed, while the peak in SSC indicates flushing of sediments from the glacier bed. Enhanced solute acquisition by these meltwaters would substantially increase proglacial EC values until the solute source was exhausted. Immediately following the chinook, therefore, proglacial EC dropped significantly due to the rapid transit of surface-derived meltwaters at reduced discharges through large channels now devoid of sediment, and the subsequent reduction in solute acquisition by these meltwaters (Tranter et. al., 1997).

Expansion of glacier drainage may also have occurred with drainage of the Crevasse Lake at 10.00h on JD213. High melt rates during the chinook would have input sufficient water to the Crevasse Lake to cause a rupture at the base of the crevasse, and subsequent connection with the bed (Scambos et. al., 2000).

The effects of chinook events on glacier-fed rivers can be significant. A drop in water temperatures due to sudden influx of cold glacial meltwater, in combination with enhanced sediment transport due to expansion of subglacial drainage, may alter river ecology and affect benthic communities (McGregor et. al., 1995). In addition, the removal of the cryoconite layer with its associated sediment, microbial communities, organic carbon and nutrients could provide an important stimulus to subglacial ecosystems and proglacial river communities (Vincent et. al., 2000).

Recurrence interval

Both the local meteorological record and Keimig’s (unpub. data) synoptic classification indicate that these local and synoptic conditions are very rare. This suggests that the chinook has a relatively infrequent recurrence interval at the study site, and as such its impacts will be related mainly to glacier hydrology, and the effects on mass balance would be minimal.

CONCLUSION

A chinook event occurred in the Canadian high Arctic during the period 28-30 July, 2000. It had a significant impact on melt, enhancing turbulent heat fluxes and increasing melt during the event to approximately 27% of total seasonal melt at the upper weather station. The high melt rates increased supraglacial flow efficiency, as evidenced by the drop in relative stage to lower than pre-event levels immediately following the stage peak, at all three supraglacial monitoring locations. They also contributed to glacier drainage expansion, as evidenced by the opening of up-glacier moulins and the drainage of the Crevasse Lake. This illustrates that extreme melt events associated with specific synoptic conditions can generate runoff events large enough to expand and enlarge glacier drainage systems, and could also have an effect on glacially-fed rivers.

Calculation of melt using the degree-day method results in an underestimation of both total seasonal and event-related melt amounts, indicating that this method is unreliable in areas where such events occur. Examination of the recurrence of the synoptic configuration that created the chinook suggests a low incidence rate, and we therefore assume that the chinook is more important for glacier hydrology than glacier mass balance.

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