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Climatic influences on streamflow and sediment flux into Lake C2, northern Ellesmere Island, Canada *

Douglas R. Hardy
Dept. of Geosciences, University of Massachusetts, Amherst, MA 01003, USA

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Abstract

Streamflow, suspended sediment transport and meteorological variables at two elevations were measured through the 1990–1992 field seasons at Lake C2, northern Ellesmere Island, as part of the Taconite Inlet Lakes Project. The objectives were to determine the extent to which suspended sediment flux responded to climatic variability, and to ascertain which meteorological variable was most strongly associated with daily discharge and sediment load. This study provided a partial test of our hypothesis that the annually-laminated sediments of Lake C2 contain a paleoclimate signal. Streamflow to the lake was almost exclusively the result of snowmelt, in response to inputs of atmospheric energy as measured by air temperature at the median watershed elevation (520 m). Sea-level air temperature, global solar and net all-wave irradiance were less clearly associated with discharge. Fluctuations of discharge and suspended sediment concentration were nearly synchronous, and non-linearly related. Daily sediment discharge was therefore linked by streamflow, with a time lag, to the energy available for snowmelt. Mean daily air temperature and cumulative degree-days above 0 °C, at 520 m elevation, were successfully used to predict the daily and seasonal discharge of runoff and sediment to the lake.

Introduction

In Canadian High Arctic watersheds (i.e. north of 75°), streamflow occurs for only a brief period of weeks to months each summer, primarily as a response to the melting and runoff of accumulated winter snowfall. In association with the annual snowmelt flood, sediment is transferred from the landscape to stream channels, and ultimately to sites of deposition such as lakes and estuaries. Snowmelt processes, and their linkage with channel processes, are of paramount importance in determining the magnitude and timing of peak annual discharge, as well as the total annual sediment load, transferred from watersheds in the region (Figure 1).

Previous investigations of High Arctic streamflow processes have emphasized certain geographical areas, been of limited duration, and have largely neglected suspended sediment monitoring. The majority of basins studied have been within the Arctic Lowland or Parry Plateau physiographic regions of the southern Queen Elizabeth Islands. For the entire High Arctic, hydrographs for more than three years have been published for only two rivers, on Cornwallis Island (see Cogley & McCann, 1975; Woo, 1983). With only a few exceptions (McCann *et al.*, 1972; Woo & Sauriol, 1981; Lewkowicz & Wolfe, 1994; Hardy, 1995), suspended sediment monitoring has been at low resolution, typically less than one sample per day.

Many previous efforts to predict or model the annual snowmelt flood, on the basis of meteorological variables, have been hindered by the presence of snow dams (e.g. Wedel *et al.*, 1978; Woo, 1983). Within the southern Queen Elizabeth Islands, early-season meltwater runoff commonly is impounded within incised stream valleys, by deep deposits of wind-redistributed snow. The streamflow response when the dam eventually fails is decoupled from the snowmelt processes (Xia & Woo, 1992).

* This is the third in a series of papers published in this issue on the Taconite Inlet Lakes Project. These papers were collected by Dr R. S. Bradley.

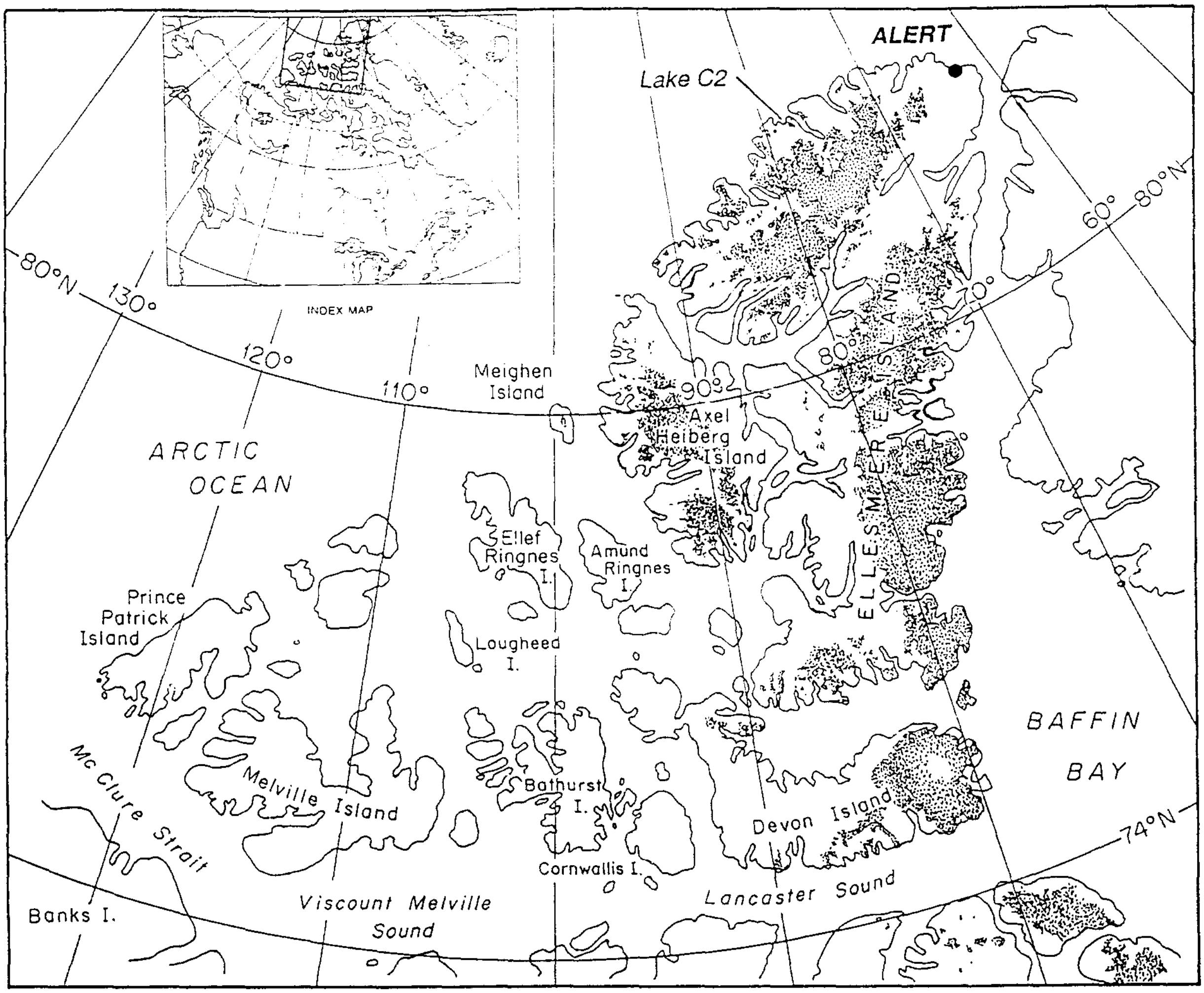

Figure 1. Location of the Taconite Inlet Lakes study area, and the Queen Elizabeth Islands. Glaciers are indicated by stippled shading. The distance from Lake C2 to Alert is ca. 250 km.

This paper examines relationships between the fluxes of runoff and suspended sediment into Lake C2, northern Ellesmere Island, and meteorological variables measured within the watershed. A principle objective of the study was to determine whether daily values of a meteorological variable could be used to predict daily discharge and sediment transfer into the lake, over three years. This investigation provided one test of a hypothesis which guided the Taconite Inlet Lakes Project, that annual sediment thickness in Lake C2 could provide a longterm proxy record of paleoclimate for northern Ellesmere Island.

The Taconite Inlet Lakes Project was an intensive campaign to understand processes controlling the variability of lacustrine sedimentation (Bradley *et al.*, 1996). Lake C2 sediments are almost entirely clastic and annually-laminated; their structure, we believe, contains the paleoclimatic signal (Hardy *et al.*, 1996). Processes controlling sedimentation were studied both within the watershed (this study) and within the lake, as varve interpretation cannot be accurately accomplished without knowledge of both systems (cf. Perkins & Sims, 1983 and Stihler *et al.*, 1992). Lacustrine investigations encompassed the physical and chemical limnology (Ludlam, 1996), diatom ecology (Ludlam *et al.*, 1996), and sediment distribution and deposition patterns (Retelle & Child, 1996). Multiple sediment cores were recovered from the lakes, and used to establish the annual nature of the laminae (Zolitschka, 1996), and to analyze the variability of their thickness through time (Lamoureux & Bradley, 1996).

Study site

Lake C2 is adjacent to Taconite Inlet (82°50′ N; 78°00′ W), on the north coast of Ellesmere Island, Canada (Figure 1). The study watershed encompasses 21 km^2 of mountainous terrain, has 1200 m of relief, and provides the only significant inlet to Lake C2 (Figure 2). Although approximately 9 percent of the watershed is glacierized, field evidence indicates that the glaciers are cold-based, and are not an important control on sediment supply. Streamflow is dominated by runoff of the seasonal snowcover as it melts, which is quickly routed to the lake by steep valley slopes and steep channel gradients. Minimal vegetation cover exists, and the watershed has not received human influence.

Methods

Data collection at the field site, and the analysis as detailed below, was designed to permit calculation of daily streamflow volume and suspended sediment mass, resulting from daily atmospheric energy inputs (as indicated by standard meteorological variables). As in many watersheds with seasonal snowcover or ice masses, a time delay or lag existed between the diurnal fluctuation in energy inputs and the melt-controlled diurnal cycle of discharge. This lag has been shown to vary seasonally, in response to the changing distance from snowmelt sources (e.g. Woo, 1976), stream channel characteristics, and other factors. Nonetheless, estimation of daily discharges in this study required a generalized lag value (in hours), which indicated the total 24-h discharge resulting from energy input during the preceding day (i.e. total discharge between successive daily minima).

Daily hydrological values were determined as follows: (1) collection of hourly meteorological data at two sites; (2) synthesis of hourly time series of discharge and suspended sediment concentration (SSC), from measurements and interpolation; (3) investigation of lags between pairs of input-output variables, based on the hourly time series; and (4) selection of an generalized lag, allowing calculation of daily discharge and suspended sediment load (SSQ). Finally, the strength of association between these daily hydrological variables and average daily meteorological variables was assessed.

Two automated weather stations were used in this study. Delta was operated through each field season, 1990–92, on the Lake C2 delta, at 7 m above sea level (a.s.l.). A second station, hereafter termed Echo, was operated at the median watershed elevation of 520 m a.s.l., during 1991 and 1992 (Figure 2). Table 1 details the variables measured and data recorded. Measurements and calculations were made by Campbell Scientific 21X dataloggers. The Delta site was selected to allow comparison of weather data from Taconite Inlet with measurements recorded at High Arctic stations of the Canadian Atmospheric Environment Service (AES), all of which are located close to sea-level. The Echo site was at the crest of a broad peak, and more representative of the watershed. Roughly two-thirds of the total area was within 200 m elevation of Echo.

All hydrological measurements were made at a gaging station on the Lake C2 delta (Figure 2; Table 2). Profiles of velocity and depth were measured at the same cross-section each season ($n = 47$ to 84), over the full range of stage. Velocity was measured at six-tenths water depth using a Swoffer Instruments model 2100 current meter. Discharge was calculated by the mid-section method (Rantz *et al.*, 1982). Rating curves were fit to the plotted stage-discharge measurements using least squares regression (standard error <0.01 to 0.04 $m^3\ s^{-1}$), and hourly discharge values were calculated from the hourly stage series.

Suspended sediment was sampled by depth-integration, using a US DH-48 sampler. Typically, one vertical was integrated each sampling time in 1990, which increased to two at the end of 1991 (Table 2). In 1992, three verticals were sampled each time using the equal-discharge-increment (EDI) method (Edwards & Glysson, 1988). Through all years the sampling interval was variable, depending on discharge and the visually observed rate of change in SSC. The least intensively sampled season was 1990 ($n = 90$ sampling times), with one to 17 sampling times per day, except during very low flows when only one sample was taken every couple of days. During 1992, samples were often taken hourly, and always continued several hours past the daily peak ($n = 333$ sampling times, three verticals each). Suspended sediment samples were vacuum filtered, air dried, and packaged in the field, then weighed in the lab after drying 30 min at 50 °C. The following filter types (with minimum size retention) were used: 1990, Whatman 541 (20–25 μm) and Millipore HA (0.45 μm); 1991, Whatman 934-AH (1.5 μm)

Table 1. Weather station data collection programs, 1990-92. Sensor heights are over snowfree ground

	Field season	Variable (sensor ht.) (units)	Sampling/sensing frequency	Logged information
Weather station Delta	1990-92	Precipitation (mm)	12 h total (plus event obs.)	12 h total
		Wind speed (2.5 m) (m s^{-1})	1 min	1 h mean wind speed/vector magn.
		Wind direction (2.5 m) (degrees)	1 min	1 h mean wind vector dir. & S.D.
		Air temperature (2 m) (°C)	1 min	1 h mean
		Relative humidity (2 m) (%)	1 min	1 h mean
		Global irradiance (1 m) (W m^{-2})	1 min	1 h mean
		Sea level pressure (1 m) (mb)	1 min	1 h mean
	1991-92	all above, plus:		
		Ground temp. (−0.5 m) (°C)	1 min	1 h mean
		Net irradiance (1 m) * (W m^{-2})	1 min	1 h mean
	1992	all above, plus:		
		Vapor pressure (2 m) (mb)	1 min calculation	1 h mean
		Snow temp. (profile) (°C)	20 s	10 min mean
Weather station Echo	1991-92	Wind speed (2.5 m) (m s^{-1})	1 min	1 h mean wind speed/vector magn.
		Wind direction (2.5 m) (degrees)	1 min	1 h mean wind vector dir. & S.D.
		Air temperature (2 m) (°C)	1 min	1 h mean
		Relative humidity (2 m) (%)	1 min	1 h mean
		Global irradiance (1 m) (W m^{-2})	1 min	1 h mean
		Net irradiance (1 m) * (W m^{-2})	1 min	1 h mean
	1992	all above, plus:		
		Ground temp. (−0.1 m) (°C)	1 min	1 h mean
		Vapor pressure (2 m) (mb)	1 min calculation	1 h mean
		Snow temp. (profile) (°C)	20 s	10 min mean

* Measured in 1991; calculated from measured components in 1992.

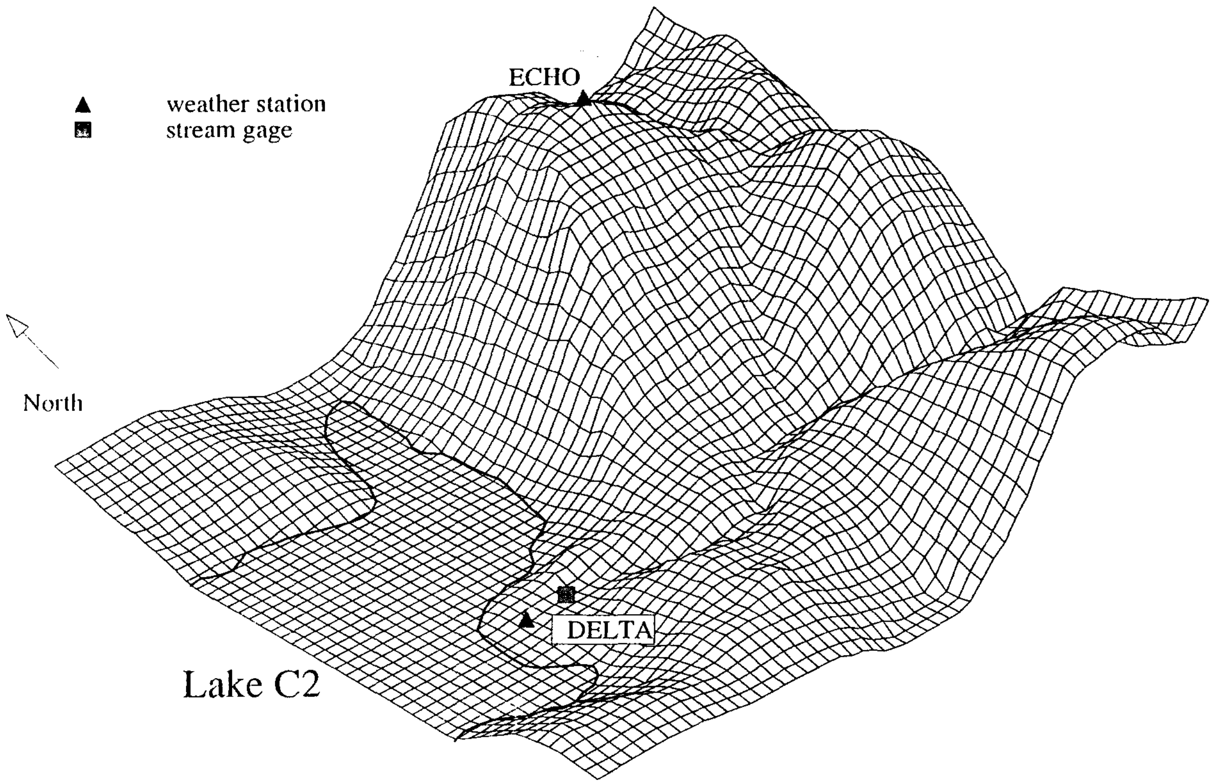

Figure 2. The western portion of the Lake C2 watershed, viewed from 31° above the horizon, and from an azimuth of 225° true. Grid spacing is 50 × 50 m; vertical exaggeration is × 2. Delta and Echo weather stations were at 7 m and 520 m, respectively.

Table 2. Stream data collection programs, 1990-92

	Field season	Variable (units)	Sampling/sensing frequency	Logged information
Stream station	1990	Stage (cm)	0.5–8 h (staff observations)	same
		Water temperature (°C)	8–24 h	same
		SSC (mg l^{-1})	1–48 h (n = 1 vertical)	same, plus visual obs. at each stage meas.
	1991	Stage (cm)	continuous chart	1 h sample
		Water temperature (°C)	1 min	1 h mean
		SSC (mg l^{-1})	1–24 h (n = 1-2 verticals)	same, plus obs.
	1992	Stage (cm)	continuous chart	1 h sample
		Water temperature (°C)	1 min	1 h mean
		SSC (mg l^{-1})	1–8 h, plus obs. (n = 3 verticals)	same, plus obs.

and Millipore HA (0.45 μm); 1992, Whatman WCN (0.45 μm). For all years, the upper size limit of suspended sediment samples was truncated at 2 mm during processing, by sieve. A broad size range was utilized in this study, as the sand fraction (0.063 to 2 mm) is an important component of the Lake C2 varves.

Through the streamflow period of each field season, a time series of hourly SSC values was synthesized from plots of the measured concentrations. The 1990 measurement record contained temporal gaps of up to 48 hours; these were filled using suspended sediment rating curves, developed from time-specific subsets of the 1990 measured values ($r^2 = 0.85$, 0.65, 0.92). SSC sampling frequency in 1991 and 1992 was proportional to the rate of change in SSC (up to 17 hours daily), which allowed gaps in the time series to be filled using linear interpolation between measured values more than one hour apart, except on isolated occasions when field observations suggested a slight deviation.

Results

Each of the 1990–92 field seasons at Taconite Inlet began prior to streamflow commencement. Once streamflow began, hydrological measurements were made over 38 to 49 days, until the end of each field season. The results detailed below, and their interpretation, therefore refer only to these field periods, as monitoring ceased upon departure of personnel from the site. An estimate of weather and hydrologic activity after each field season was made based on data from nearby weather station Alert (Figure 1). At the end of the 1990 season, snowcover in the watershed was greatly reduced, and the mean daily temperature dropped significantly three to four days later. When the 1992 season concluded, evidence in the watershed and from the Alert data suggests that winter had begun. In contrast, considerable snow accumulated through the 1991 field season, supplementing residual winter snow. Peak annual discharge probably occurred during one of two very warm intervals, therefore, following the field season.

Summer climate at Taconite Inlet

Daily values of meteorological variables through each field period provide an indication of the summer climate at Taconite Inlet (Figure 3). The severity of the current climatic regime is demonstrated by the low values of net radiation and low temperatures, as well as the frequency of summer snowfall (Figure 3). Frequently, the atmospheric freezing level migrated within the range of watershed elevations, resulting, for example, in blowing snow in the upper catchment area and drizzle or rain at sea level.

Global radiation receipts were highest early in each season (Figure 3, 1990–92a). This was a function of less cloud cover, due both to limited local moisture sources and less moisture advection from lower latitudes. During 1991 and 1992, streamflow began shortly after the average daily net irradiance became positive (Figure 3).

Mean daily air temperature at both sites fluctuated relatively slowly (Figure 3, 1990–92b). These multi-day temperature fluctuations were greater than the diurnal variation, and often crossed the 0 °C threshold. As with radiation, fluctuations at this timescale were in response to synoptic weather patterns. Air temperature early in the 1992 season was considerably lower than early in 1990 or 1991, which delayed the initiation of streamflow. (Mean temperatures each year at Delta for the overlap period June 9–19 were 0.5, 0.7 and −2.1 °C.)

Temperature measurements at the upper elevation weather station (Echo) revealed frequent temperature inversions (Figure 4). Defined conservatively as no difference in temperature with height, inversion conditions were very persistent, averaging 4 days in length in 1991, and continuing for 9 days on one occasion in 1992. The significance of these inversions is discussed below.

Streamflow into Lake C2

Within the discharge and SSC time series, both diurnal and seasonal fluctuations were evident (Figure 5), the magnitudes of which varied through each field season. The diurnal pattern of discharge suggests that runoff was governed by the atmospheric energy available for snowmelt, and SSC fluctuations indicate a general dependence of SSC on discharge. The diurnal fluctuations of SSC also demonstrate the importance of hourly resolution sampling, especially during the days of highest discharge (cf. Clark *et al.*, 1988; Hardy, 1995). The pattern of seasonal fluctuations in discharge was broadly consistent over the three years, in that multi-day intervals of very low discharge alternated with intervals of high discharge. The delineation of subperiods (Figure 5) was done on the basis of abrupt changes in discharge that were not due to diurnal fluc-

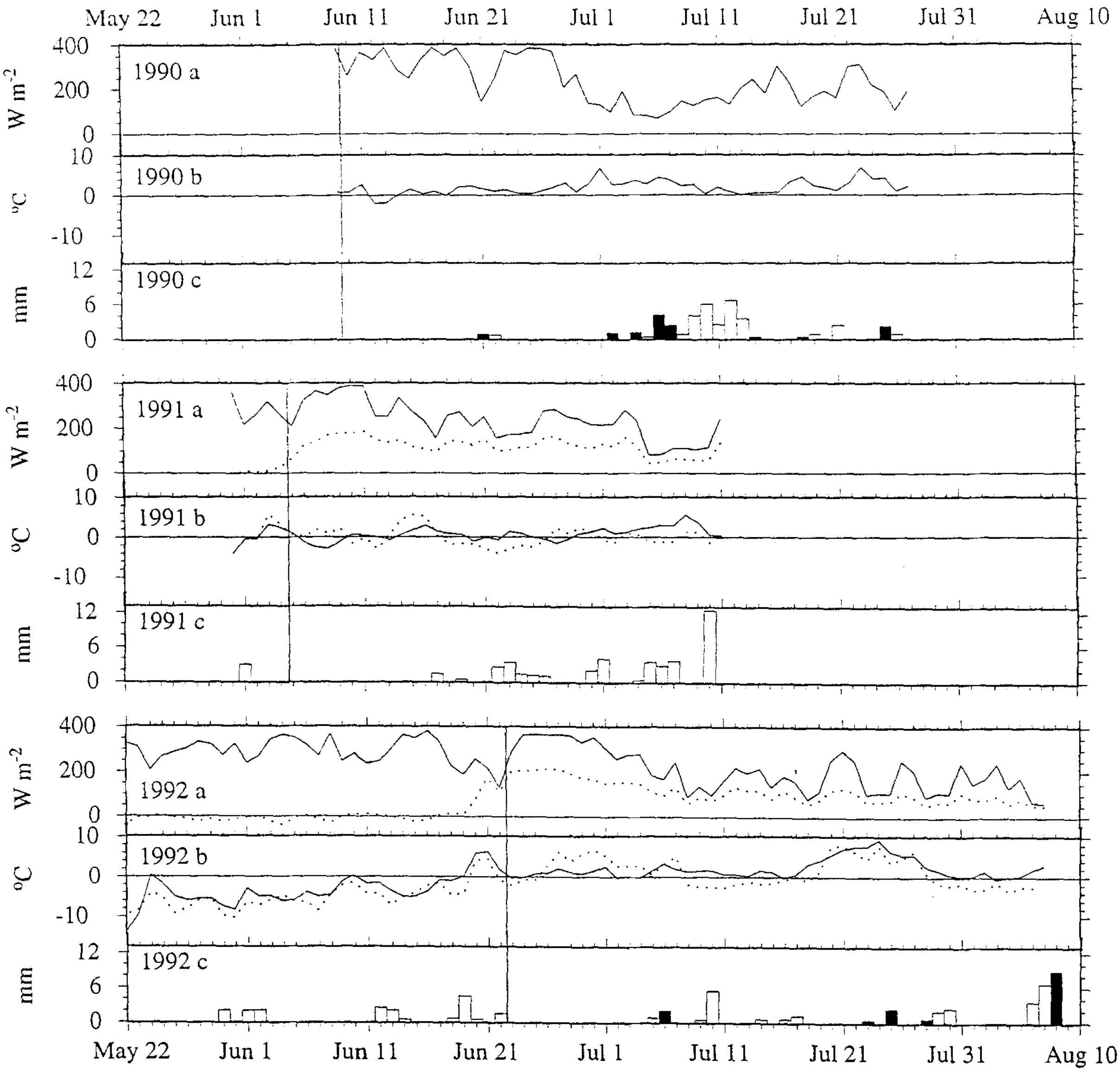

Figure 3. Mean daily values of meteorological variables, 1990–92. (a) global solar (solid line) and net all-wave (dotted line) irradiance at Delta (global only in 1990); (b) Delta (solid) and Echo (dotted) air temperature (Delta only in 1990); and (c) total daily precipitation at Delta (black bars = rain; white = snow or mixed). Vertical lines indicate the first day of streamflow each year; horizontal lines are a zero reference in plots (a) and (b).

tuations. Subperiods have often been employed to analyze relationships between climatological and hydrological variables in glacierized catchments (cf. Østrem, 1975; Gurnell *et al.*, 1992; Clifford *et al.*, 1995). In this study, the high discharge subperiods (H1, H2 in Figure 5) represent intervals of rapid snowmelt, and were of greatest importance to sediment transfer.

A significant proportion of the total annual sediment load each year was delivered within a very short period of time. This is illustrated in Figure 6, the 1992 sediment discharge series (SSQ, the product of discharge and SSC). Fifty-five percent of the annual load was transferred during only one percent of the time (i.e. 3 to 4 of 365 days). Although this proportion falls within the range of 40 to 60% for most rivers of North America (Meade *et al.*, 1990), ninety-nine percent was transferred during 5% of the time, which represents the relatively brief snowmelt flood, charac-

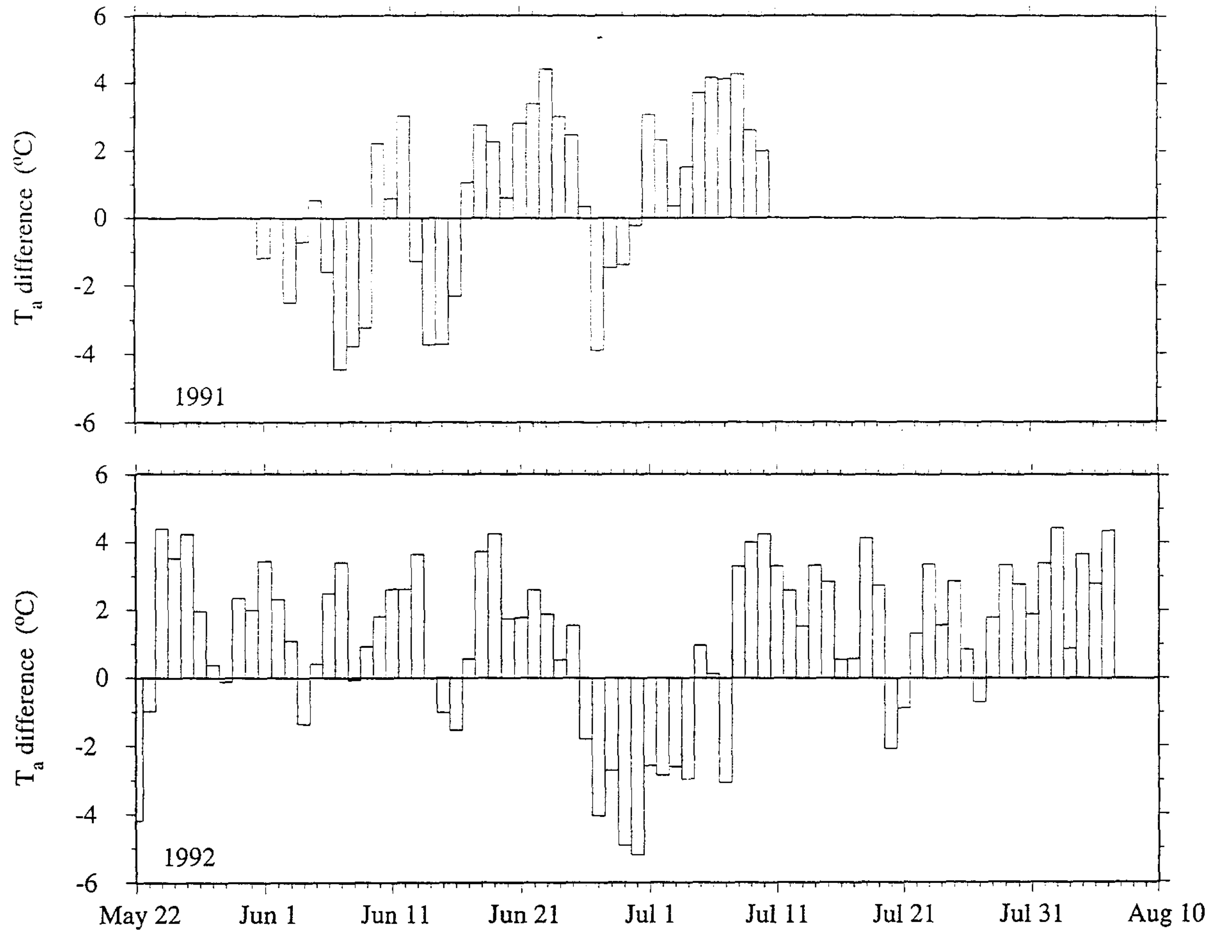

Figure 4. Mean daily air temperature difference between Delta and Echo weather stations, 1991 and 1992. Negative differences indicate inversion conditions, when Echo (520 m) was warmer than Delta (7 m).

teristic of the High Arctic. This finding is particularly important to the interpretation of the Lake C2 sediment record. It indicates that the annual increment of sediment delivered to the lake is primarily a representation of processes which occur over only a few days each year.

Hourly weather and discharge associations

Temporal patterns were examined within each of the time series, and between pairs of variables. This provided information about the consistency of the streamflow response to atmospheric energy inputs (i.e. the validity of a fixed lag value). Autocorrelation and cross-correlation statistical techniques were used for this purpose, the details of which will be reported elsewhere. In this section, only the salient results related to selection of a generalized lag are presented. In accordance with the paleoclimatic objectives of the Taconite Inlet Lakes Project, the weather variables considered were proxy measures of atmospheric energy input. These were used rather than energy balance terms (e.g. sensible heat flux) to correspond with variables measured at nearby weather station Alert (Figure 1), where temperature and radiation measurements began in 1950 and 1964, respectively. The input variables considered were incoming short-wave (global) radiation, net all-wave radiation, and air temperature, from the two weather stations in the watershed. Discharge was the output variable, and patterns were investigated through subperiods and over each entire field season.

Among the input variables examined, air temperature at the median watershed elevation was most strongly and consistently associated with discharge.

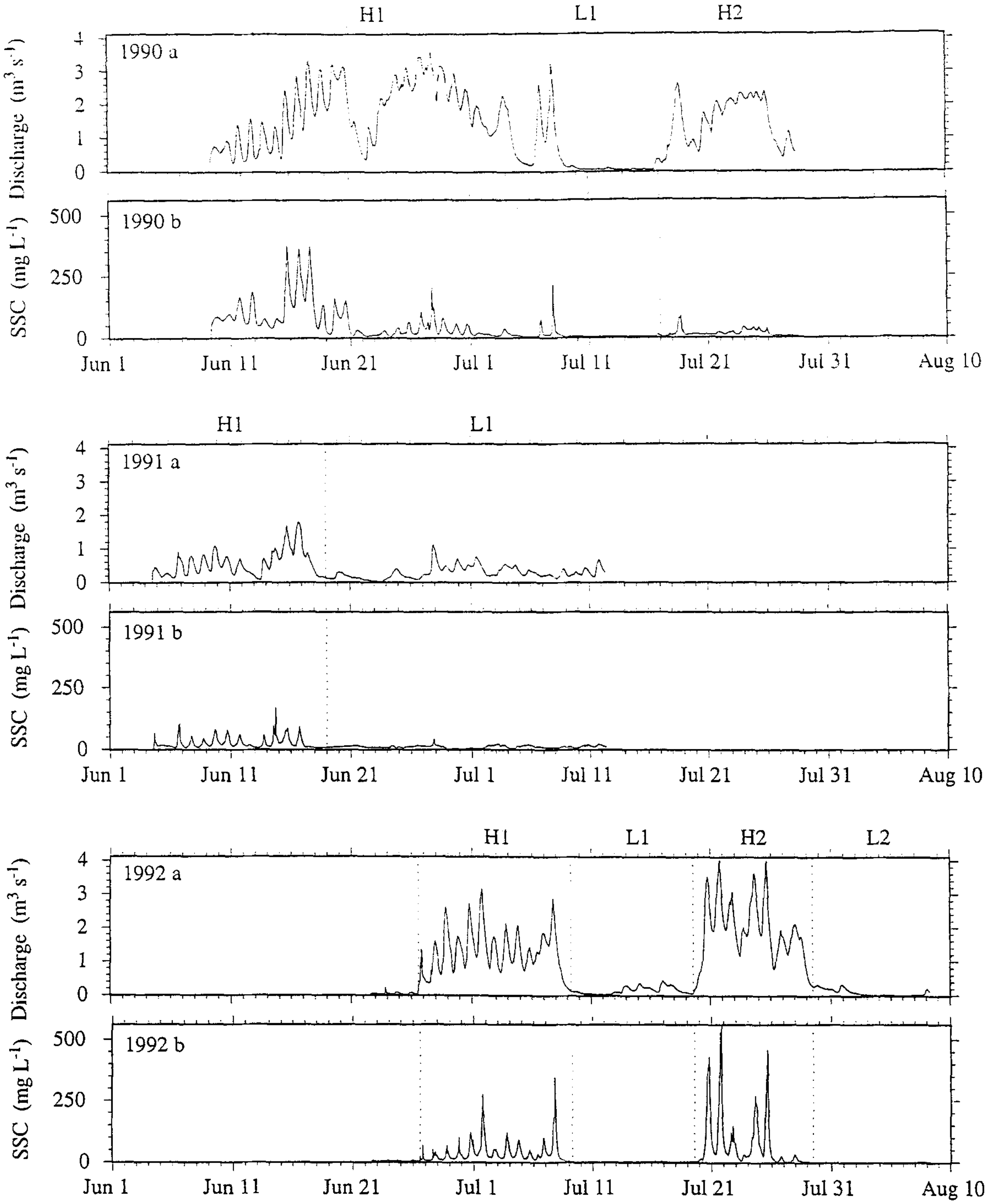

Figure 5. Hourly time series through each of the 1990–92 field seasons, of (a) discharge; (b) suspended sediment concentration (SSC). Vertical dotted lines delineate subperiods of high and low discharge.

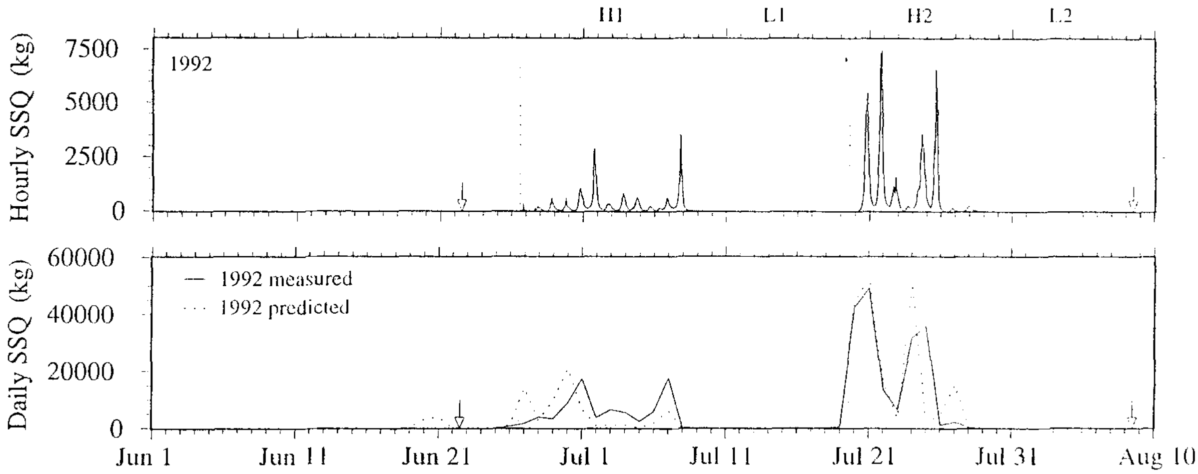

Figure 6. Hourly (top) and daily (bottom) time series of suspended sediment discharge (SSQ), through the 1992 field season. Arrows mark the beginning of streamflow and end of the field season. Predicted SSQ values (bottom) are based on Echo air temperature, beginning June 1 (see text). Vertical dotted lines delineate subperiods of high and low discharge.

The strength of association was not very sensitive to the exact lag imposed, due to minimal 24-h periodicity in the Echo temperature time series. Sea-level temperature, in contrast, was less well associated with discharge at any lag. The lag of discharge behind radiation was always clearly indicated, due to the diurnal fluctuations of both. The strengths of association at the best-match positions, however, were less than those for Echo temperature and discharge.

Discharge and SSC association

The dependence of SSC on discharge is illustrated in Figure 5. This linkage was investigated by searching for any systematic differences in the timing of fluctuations (i.e. leads or lags), and by examining the stability of the discharge-SSC relation. Two examples from other regions demonstrate systems where suspended sediment flux prediction would be extremely difficult or impossible, even if weather and discharge were strongly associated. In subarctic Finland, Threlfall (1987) found the lag of SSC behind discharge to be variable, at between 2 and 42 h. On Cornwallis Island, within the Queen Elizabeth Islands, Woo & Sauriol (1981) identified no coherent relation between discharge and SSC. At Lake C2, however, cross-correlation functions showed the diurnal fluctuations of discharge and SSC to be consistently in-phase. The strongest association was found at no lag, through all subperiods and through each full field season.

Variability in the relationship between values of discharge and SSC has at least two sources (Figure 7). First, seasonal hysteresis is evident in the relationship between the two high flow subperiods of 1992 (clockwise looping). Less well developed looped relations were also present through the diurnal fluctuations each day (not shown). At both timescales, looping most likely demonstrates variation in the supply of sediment (cf. Meade *et al.*, 1990). Second, SSC was higher through the 1991 field season. This was probably due to the prolonged early-season period of relatively low discharge, which preceded the annual peak.

Calculation and prediction of watershed outputs

Analyses of the hourly weather and discharge time series demonstrated a fairly consistent lag in the delivery of snowmelt to Lake C2. Furthermore, SSC was found to fluctuate in phase with discharge. These findings indicated that daily totals of both discharge and suspended sediment could be estimated from the hourly series, for all three years, using a generalized lag. Nine hours was selected as the most appropriate lag.

The application of a generalized and constant lag represents an over-simplification of the physical processes involved. In reality, the discharge lag will vary according to the meltwater source area location in the watershed, and where energy inputs at a point are measured. The lag associated with each source area will also vary through time, as hillslope drainage

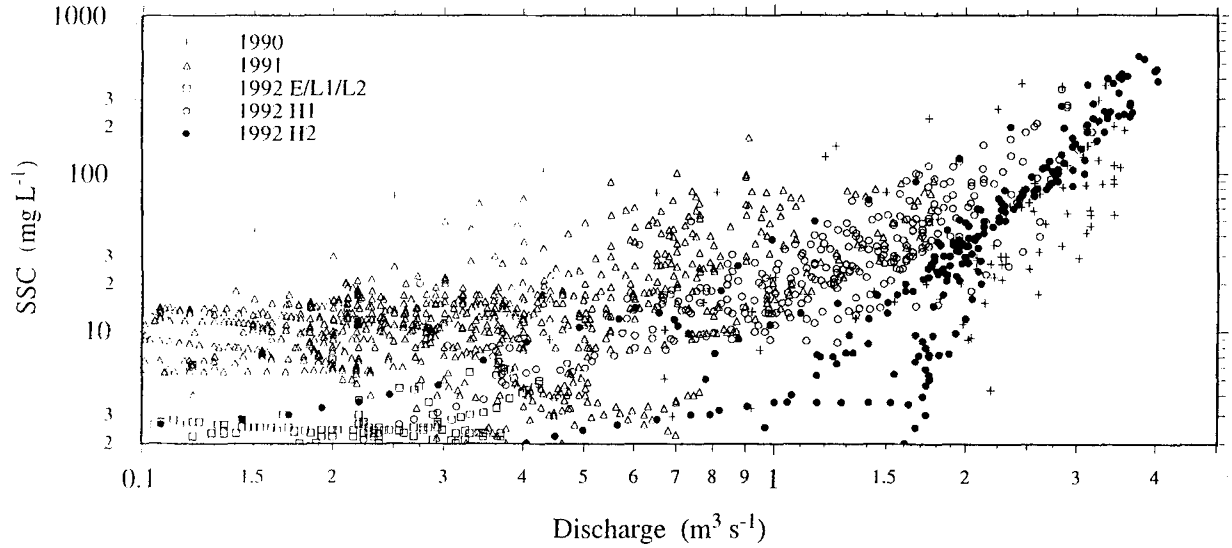

Figure 7. The relationship between SSC and discharge. Measured values only are plotted for 1990 ($n = 90$). Values for 1991 and 1992 are subsets of the synthesized time series, where SSC>2 mg l^{-1} and discharge>0.1 m^3 s^{-1} (n=795 of 905 [1991]; 617 of 1115 [1992]). Subperiods of the 1992 field season are distinguished.

develops and the channel flow velocity changes. For these reasons, integrated watershed outputs cannot be completely represented by point measurements and a constant lag. Nonetheless, several factors unique to the Lake C2 watershed indicate generalization was warranted, including uniform and high gradient valley slopes, minimal detention storage of meltwater, and a data collection site representative of a large proportion of the basin (i.e. Echo).

The relative capacity of different daily meteorological variables to predict daily streamflow and sediment transfer is indicated in Figure 8. Echo air temperature emerged as the input variable most closely associated with discharge, and hence discharge of sediment into the lake. Daily watershed outputs, estimated by least squares regression using the pooled 1991 and 1992 data sets of Echo temperature ($n = 134,83$), were:

$$\text{Discharge} = 20294 \times e^{(0.36 \times \text{Echo Ta})} \quad (r^2 = 0.75)$$

$$\text{SSQ} = 143.9 \times e^{(0.74 \times \text{Echo Ta})} \quad (r^2 = 0.70)$$

The ability of the empirical relationship above to predict daily sediment discharge is illustrated in Figure 6. While the timing of sediment delivery peaks is off somewhat early in the season, there is little difference between the measured and predicted sediment transfer through the two high flow subperiods.

Prediction of cumulative outputs

The varved sediment record from Lake C2 provides annual resolution (Zolitschka, 1996). The thickness of each laminae is therefore a measure of the cumulative sediment transfer that year. While each laminae may also contain sublaminae resulting from the most significant multiday periods of sediment discharge each year, these currently cannot be recognized due to their submillimeter thickness. To further examine the ability of Echo temperature to predict streamflow and sediment discharge, cumulative values were also considered.

Figure 9 illustrates cumulative discharges through the 1991 and 1992 field periods, as a function of cumulative degree-days above 0 °C at Echo (Echo MDD). The watershed outputs increase as a nearly linear response to cumulative degree-days:

$$\Sigma 1991\ Q\ (10^6\ m^3) = 0.03\ (\text{Echo MDD}) - 0.28 \quad (r^2 = 0.98)$$

$$\Sigma 1992\ Q\ (10^6\ m^3) = 0.03\ (\text{Echo MDD}) - 0.44 \quad (r^2 = 0.99)$$

$$\Sigma 1991\ \text{SSQ}\ (10^3\ kg) = 0.84\ (\text{Echo MDD}) - 4.83 \quad (r^2 = 0.95)$$

$$\Sigma 1992\ \text{SSQ}\ (10^3\ kg) = 2.98\ (\text{Echo MDD}) - 67.11 \quad (r^2 = 0.95)$$

The x-intercept of the 1992 plot is known with certainty, as meteorological measurements began 5 weeks prior to streamflow; for 1991, measurements began May 30, and any earlier degree-days would shift the

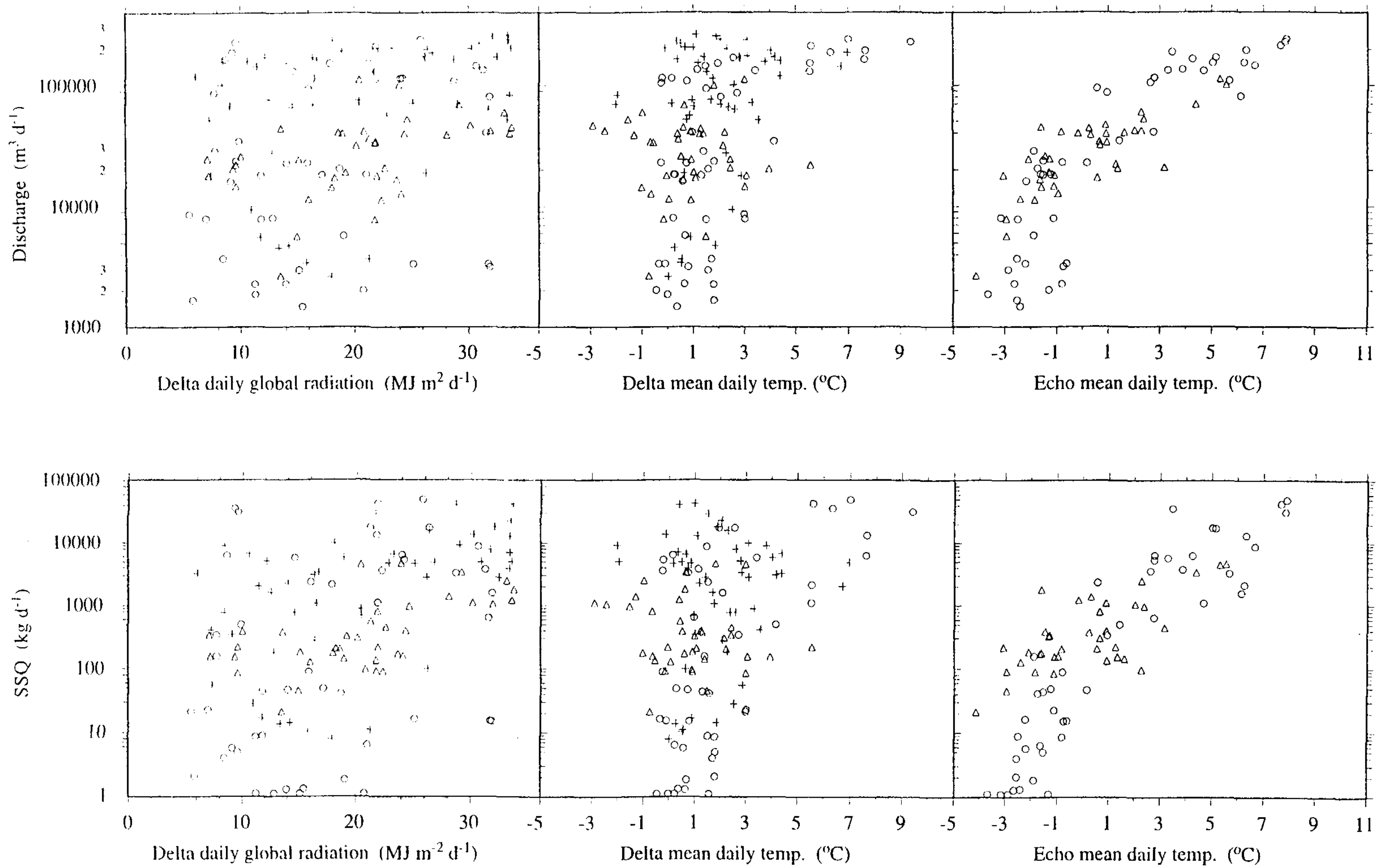

Figure 8. Daily discharge (top) and SSQ (bottom) totals calculated using a nine hour lag, plotted against Delta daily global radiation (left), Delta mean daily air temperature (center), and Echo mean daily temperature (right). Symbols: + = 1990; Δ = 1991; ο = 1992.

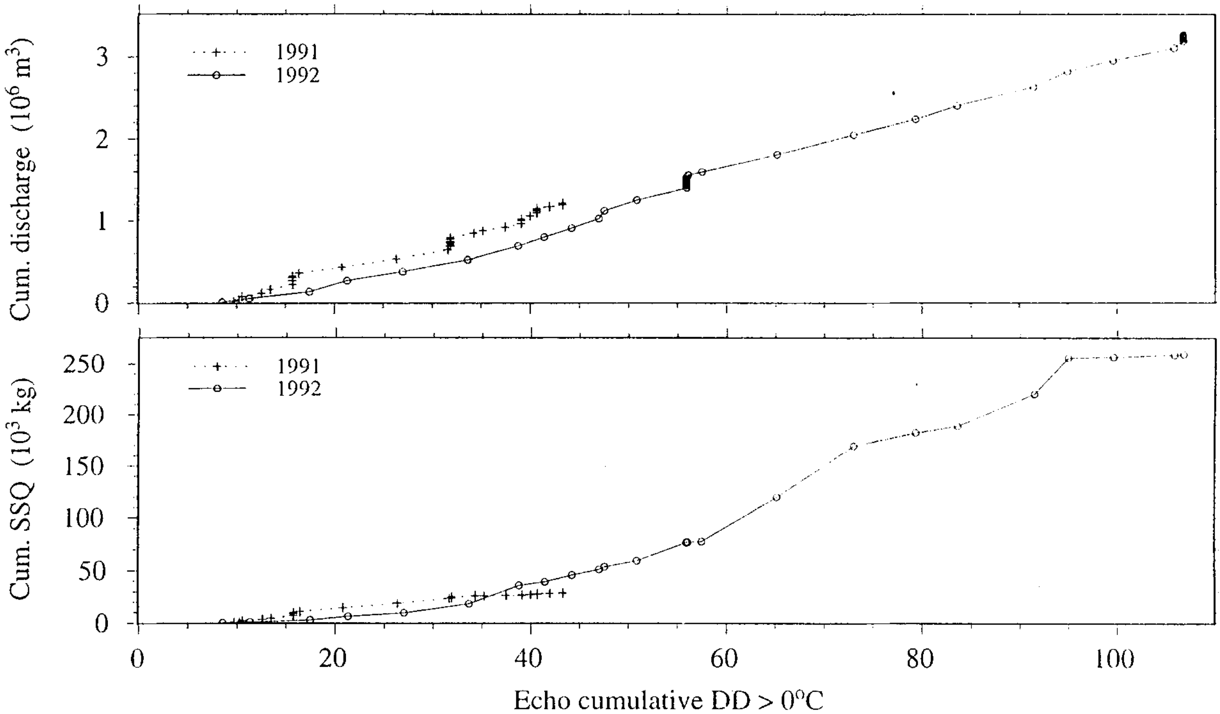

Figure 9. Cumulative discharge (top) and SSQ (bottom), and cumulative degree-days at Echo, for the 1991 and 1992 field periods. Weather measurements in 1991 began June 1 and may have missed some days with positive mean temperatures; measurements in 1992 began 27 days before the mean daily temperature was above freezing. The 1991 field season included approximately 30 percent of the total MDDs measured at Alert.

plot to the right. Such a shift would bring the subparallel cumulative discharge plots into yet better agreement. Although the magnitude and pattern of 1991 and 1992 discharge differed (Figure 5), Figure 9 demonstrates that cumulative watershed outputs both years responded to cumulative degree-days.

Discussion

There are few colder locations where streamflow occurs, in either hemisphere, than northern Ellesmere Island. Lakes remain perennially ice-covered, glaciers extend to sea level, and mean annual temperatures are comparable to those in the dry valleys of Antarctica (Doran *et al.*, 1994). Streamflow is dominated by snowmelt runoff, and is exclusively so some years; therefore, streams flow only on the warmest days each summer.

The results of this investigation provide new information about the influence of climate on hydrological processes in polar regions. Other studies of this type have been limited almost exclusively to glacierized watersheds, where subglacial processes and sediment sources produce more complex relationships between climate, discharge and sediment flux (cf. Lawson, 1993). A more comparable study was conducted in a 8.9 km^2 subarctic watershed without glaciers in Finland (Threlfall, 1987). Here, snow dams and river channel processes rendered prediction of basin outputs very difficult.

Air temperature as a measure of atmospheric energy input

Air temperature and radiation measurements both provide information about the energy available for snowmelt, despite the complexity of energy exchanges between the atmosphere and snow surface. At Lake C2, streamflow was clearly responsive to radiative inputs, particularly during the high flow subperiods. However, as single measures of the energy available for snowmelt, global and net radiation were not as useful as temperature. There are at least two possible explanations:

1. Radiation measurements at a point cannot reflect actual, spatially integrated, radiative exchanges. This was particularly true at Taconite Inlet. For example, through all three field seasons, the albedo of the land surface changed rapidly, both temporally and with elevation, due to frequent summer snowfall and the uneven distribution of the winter snowpack. Since changes in albedo profoundly affect the net solar irradiance, and therefore the net all-wave balance, measurements at a weather station site may not be representative of adjacent areas. In addition, the solar elevation angle was always relatively low (between 16 ° and 31 ° on the solstice), and interaction with mountainous topography also caused radiation receipts to vary spatially.

2. Turbulent heat transfer associated with air mass advection probably provided most of the energy during rapid snowmelt (high discharge) intervals. Air temperature integrates many atmospheric processes, but variations primarily reflect changes in the heat balance of the ground surface below, and advection of air masses with varying thermal conditions (Lang & Braun, 1990). The first mechanism can be measured by net radiation, as discussed above. If air temperature and wind measurements record an interval of warm air advection, additional energy is provided for snowmelt by turbulent transfer. The degree to which air temperature or net radiation correlates with discharge, with an appropriate time lag, suggests which energy source is predominant.

The discussion above may help to explain temperature differences between Delta and Echo, and the disparity in their ability to predict snowmelt. Echo surface conditions (e.g. albedo) were usually more representative of the watershed than those at Delta. In addition, temperatures at the well-exposed Echo station more accurately reflected air temperatures over more of the watershed. Delta temperatures, on the other hand, were frequently influenced by advection of cold air from the adjacent ice-covered Lake C2, and by larger-scale temperature inversions (Figure 4). Inversions have been well documented throughout the Arctic, during all seasons of the year (Bradley *et al.*, 1992), but only by rawinsonde profiles. This study indicates that the sea-level network of AES weather stations provides limited information about air temperature, and hence snowmelt, at higher elevations.

The influence of precipitation

The influence of precipitation on streamflow and sediment flux into Lake C2 must be considered uncertain. Two aspects of this issue are the interannual variability of winter snowfall magnitude, and summer rainfall. During the three field seasons, for example, streamflow directly responded only once to a rainfall event, with minimal sediment transfer (see below). However, even relatively small events could potentially produce extreme runoff, due to continuous permafrost, lack of vegetation and steep valley slopes. The findings of Østrem & Olsen (1987) and Leemann & Niessen (1994), from two different climatic regimes, suggest that unusually rainy summers are required to influence the total annual sediment flux, although these studies were both done in glacierized regions, without permafrost.

Contrary to original intentions, the winter snowpack was not surveyed over the entire watershed at the beginning of each field season. At 83° N, 'winter' snow accumulation continues to increase through the spring, and snowfall or mixed events occurred more frequently than rainfall each summer at Taconite Inlet. The Lake C2 watershed contains numerous terrain orientations and elevations, and travel was very difficult on slopes of 20° to 40°. Snow depths were extremely variable, as illustrated by a 1000 m transect across relatively uniform terrain (c.v. = 2.17; $n = 98$). Areas of perennial snow cover further complicated snow cover assessment. In watersheds such as Lake C2, winter snow accumulation might best be determined as a residual to the water balance equation. This would require accurate measurement of total annual discharge, summer precipitation, evaporative losses and any change in watershed storage.

While it may be reasonable to assume that the total annual discharge is a function of the winter snowpack, the effect of snow water equivalence on the peak annual discharge is less clear. At Taconite Inlet, the close association between Echo temperature and discharge, through two seasons, suggests that the magnitude of discharge is limited by the energy available for snowmelt, rather than the supply of snow. The maintenance of diurnal discharge fluctuations through each period supports this idea. This is an important issue, due to the brevity of the runoff period, and the non-linear relationship between discharge and SSC. If accurate, snowpack volume is less important than energy inputs to the annual sediment load delivered to the lake. Additional support for this idea is provided by analysis of Swedish varve data in Granar (1956). In that study, annual thickness is very well correlated with the corresponding annual discharge maximum (est. r-value = 0.89 for Log_{10} thickness and Q_{max}; $n = 22$).

A final issue regarding snowpack volume concerns the effect on sediment availability. On south-facing slopes of the Lake C2 watershed, early snowmelt runoff took place within the snowpack itself (Hardy *et al.*, 1992). Contact between the meltwater and the underlying slopes was therefore reduced, which reduced the energy available to thaw and mobilize sediments. In general, however, the effect of snow depth on the lateral routing of meltwater through cold arctic snowpacks is poorly understood.

Summer rainfall was not an important influence on streamflow and sediment transfer during the three years, but the long-term role is uncertain. If the magnitude of peak discharge each year is limited by the energy available for snowmelt (cf. Church, 1988), rainfall runoff may be capable of producing higher discharges, but at an unknown recurrence interval. At Taconite Inlet, the one rainfall runoff event observed produced discharge peaks on July 6 and 7, 1990 (Figure 5), in response to 4.1 and 2.4 mm of rain measured on the delta (Figure 3). Mean daily temperatures these days were 4.4 and 3.8 °C, and solar radiation was low through the period. Discharge on July 7 reached 90 percent of the 1990 snowmelt peak, and while SSC reached moderate levels, the peaks were very brief. During 1991 and 1992, a streamwater and precipitation sampling program was undertaken in an attempt to identify rainfall runoff, using a change in isotopic composition ($\delta^{18}O$). In 1992, the highest intensity rainfall occurred on July 25 (two mm in two hours), but failed to alter the $\delta^{18}O$ of streamwater, despite a significant difference in isotopic composition (rainwater $\delta^{18}O = -19.08$ and $-19.14‰$; $n = 2$; streamwater $\delta^{18}O = -26.82‰ \pm 0.14$ S.D.; $n = 12$).

Both a lack of moisture and weather station data argue against rainfall as a significant source of runoff on northern Ellesmere Island. Surface melting of the frozen Arctic Ocean provides a local moisture source, but the amount is limited by air temperature. The north coast is situated on the lee side of the British Empire Range, and thus even more isolated from moisture-laden air masses than its northern location would indicate. At Alert, the record of precipitation measurement indicates that rainfall events are generally of smaller magnitude than recorded at the three other Canadian High Arctic weather stations. Over 43 years (1951–92), the four largest one-day totals were 18.8, 18.5, 17.0, and 14.7 mm. Of 27 days with more than 5 mm, none were recorded before June 15, only four occurred during the second half of June, and more than half were after July 15. Therefore, most rainfall occurs in mid to late summer, when infiltration into the active layer may reduce runoff. The runoff observed at Taconite Inlet following a relatively minor event in 1990 cannot be overlooked, however.

Much larger rainfall events have been reported from elsewhere in the Queen Elizabeth Islands, which resulted in dramatic discharge and sediment transport. On western Axel Heiberg Island, Adams (1966) observed extreme erosion and fluvial transport of large boulders during three rain-induced floods in July 1961. Daily rainfall totals associated with the first two floods were 10.1 and 19.5 mm, and that of the largest event was not specified. Another example of rainfall flooding took place in July 1973 on south central Ellesmere Island. Cogley & McCann (1976) reported an exceptional one-day rainfall total (49.4 mm) associated with earthslides and rockfalls, and they measured SSC on the rising limb of the runoff flood at 8100 mg l^{-1}. Quite possibly, the sediment transfer due to singular events, such as these, could produce distinctive flood deposits within varve sequences which otherwise record the melting of snow or ice, and which would be recognizable as rainfall events (cf. Leemann & Niessen, 1994).

The climatic significance of total annual sediment transfer

The streamflow season at Taconite Inlet each year culminates in a brief period of high discharge, during which most of the annual suspended sediment transfer takes place. This episodic input of sediment is deposited as an annual lamination in Lake C2. The interval of time represented by each laminae is therefore not an entire year, but only a period of *days or weeks*.

Two years of empirical data have demonstrated that mean daily air temperature, at the median watershed elevation, accounts for 77 and 68% of the variance in daily SSQ (adjusted $r^2 = 0.48$, 0.85). Because only a relatively few days are most important to the total annual sediment transfer, annual SSQ must be a function of air temperature during the warmest few days. To illustrate, mean temperatures at Echo for the 1991 and 1992 streamflow periods (38 and 47 days) were 0.1 and 1.2 °C, respectively, yet total measured SSQ for the two field seasons differed by one order of magnitude (29 000 and 260 000 kg). This suggests that values of mean temperature, over even part of a season, obscure climatic differences which are important to sediment transfer. Nevertheless, the varved sediments from Lake C2 should provide a sensitive, proxy measure of each summer's highest temperatures.

The total annual sediment transfer may also provide a proxy measure of cumulative degree-days, which incorporate only those days when the mean daily temperature is above a threshold (e.g. 0 °C). Important warm intervals in this case are still linked to episodes of sediment transfer, and the association (signal) would not be reduced by extended periods through the summer when temperatures are low. Degree-day accumulations are also not subject to interannual variations in the seasonal timing of atmospheric energy input, as measured by air temperature. For example, streamflow began three weeks earlier in 1991 than 1992, yet the response to cumulative degree-days was similar (Figure 9).

Conclusions

Few catchments provide extreme seasonality in the transfer of sediment, limited influence by glaciers and a lake in which sediment deposition is preserved with annual resolution (i.e. varves). The Lake C2 watershed therefore offers the potential to provide a high resolution paleoclimate record. Despite the complex interrelationships among the processes influencing sediment transfer from the watershed, empirical relationships have demonstrated:

1. Streamflow into Lake C2 was almost entirely a response to snowmelt. Discharge was closely associated with air temperature at the median watershed elevation, where fluctuations were largely advection controlled. Important aspects of the Lake C2 watershed and climate governing this association included steep valley slopes, continuous permafrost, minimal vegetation, an adequate supply of accumulated winter snow, and infrequent rainfall events of limited magnitude.
2. Over the three seasons, SSC demonstrated a nonlinear dependence on discharge, and fluctuations of the two were nearly synchronous. The relationship between discharge and SSC varied slightly, both within each season and from year to year.
3. The flux of suspended sediment was linked by streamflow to the energy available for snowmelt. As a result, the daily and cumulative sediment discharge to Lake C2 were closely associated with mean daily air temperature, and cumulative degree-days above 0 °C, respectively, at the median watershed elevation. In 1992, Echo mean daily air temperature accounted for 85% of the variance in daily sediment discharge (adj. r^2).
4. Air temperature at sea-level was poorly associated with discharge. At Taconite Inlet and in other mountainous High Arctic watersheds, attempts to calibrate varve thickness with meteorological data from the sea-level AES weather station network are unlikely to succeed. On-site monitoring of the processes involved in the formation of varved sediments is essential.

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