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Ice-Related Data Series from Expedition Fiord, Axel Heiberg Island, Nunavut, Canada

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ABSTRACT

The mass balances of White Glacier and Baby Glacier, at 79.5° N on Axel Heiberg Island in the High Arctic of Canada, have been monitored since 1960. Photogrammetric estimates of terminus fluctuations are available for White Glacier and its larger neighbour, Thompson Glacier, from relatively frequent photographs dating back to the first recorded image in 1948. In addition, an ice-off (breakup) record for Colour Lake, located between White and Baby Glaciers, is available back to 1959. These data series, up to 1999, are presented. While the glacier records show an excess of ablation over accumulation and so suggest warming, the lake ice record and the advance of Thompson Glacier seem to indicate cooling. These records are of special significance because they are indices of conditions at nearly 80° N, where global models suggest that global warming should be most pronounced. However the large-scale significance of such local records should of course be assessed with caution.

RÉSUMÉ

Les bilans massiques des glaciers White et Baby (79,5º N) sur l'île Axel Heiberg dans le haut Arctique canadien ont fait l'objet d'un suivi plus ou moins continu depuis 1960. On a estimé par des méthodes photogrammétriques les fluctuations du front glaciaire du glacier White et du glacier voisin Thompson à partir de photographies relativement fréquentes prises depuis 1948. De plus, des indices de débâcle glaciaire au lac Colour, situé entre les glaciers White et Baby, ont été observés en 1959. Les séries de données, recueillies jusqu'en 1997, sont présentées. Si les données glaciaires indiquent que la fusion a été plus importante que l'accumulation, ce qui témoigne d'un réchauffement, les données sur la glace lacustre et l'avancée du glacier Thompson semblent par contre indiquer un refroidissement. Ces données sont d'autant plus significatives qu'elles reflètent des conditions régnant à une latitude proche de 80º N où, selon des modèles d'échelle mondiale, le réchauffement devrait être plus marqué. L'extrapolation des données locales devrait bien entendu être effectuée avec prudence.

Key Words: Glaciers, Global warming, Mass balance

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INTRODUCTION

Expedition Fiord, on the western side of Axel Heiberg Island, Nunavut, Canada (Fig. 1, Fig. 2), has been the focus of detailed scientific study since 1959 (Müller 1961, Ommanney 1987, Cogley 1999b, Adams 2000). The mass balances of White Glacier and Baby Glacier have been monitored, with gaps, throughout the period. Although the mass balance of Thompson Glacier is not available, it has been possible to reconstruct positions of its terminus and that of White Glacier for the period 1948 to present. In addition, an “ice-off” (i.e., breakup) record has been reconstructed for 1959 to the present for Colour Lake, a small non-glacier-fed lake located between Baby Glacier and White Glacier.

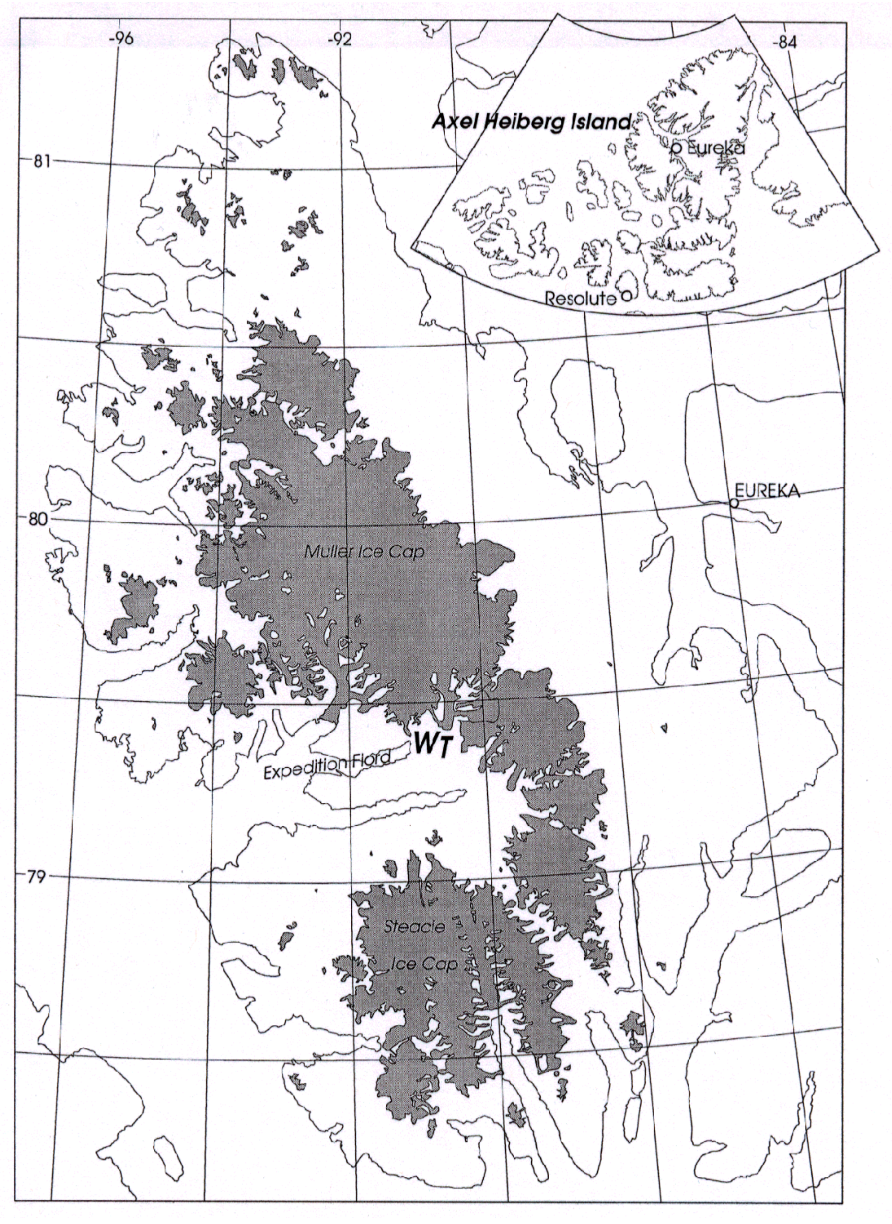

Figure 1. Axel Heiberg Island, showing the locations of Expedition Fiord, Thompson Glacier (T) and White Glacier (W).

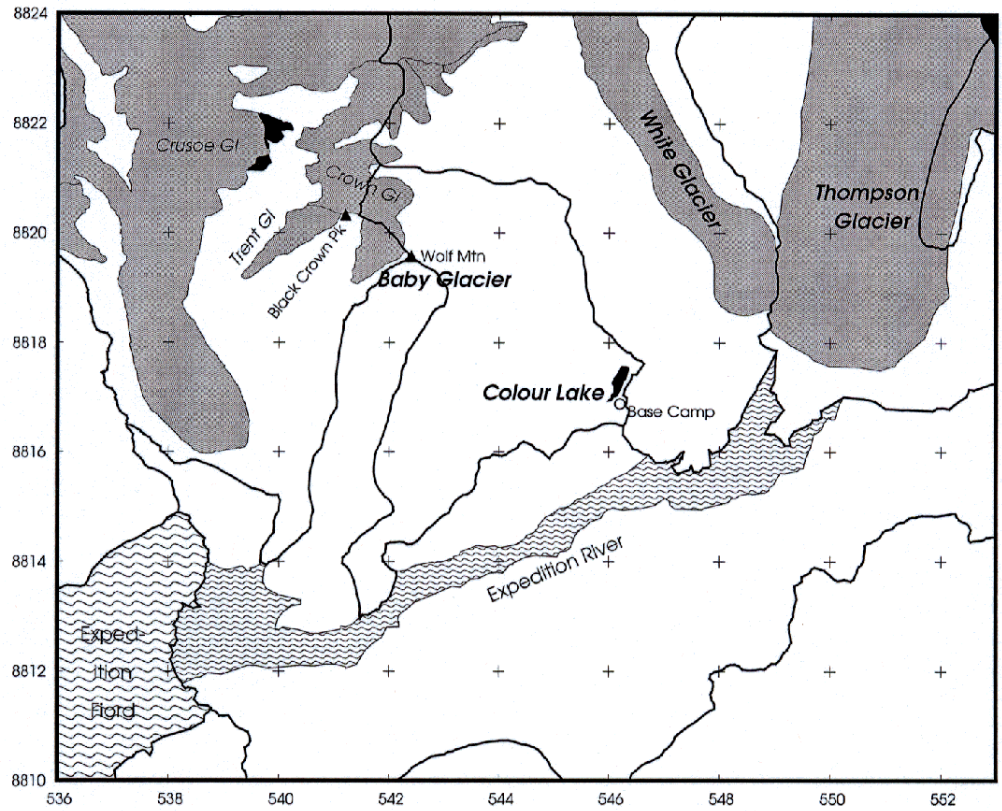

Figure 2. The head of Expedition Fiord, showing the locations of Baby Glacier, Colour Lake, White Glacier and Thompson Glacier. Thick lines are drainage divides. Coordinates, in km, are those of UTM zone 15.

Each of the data series can be considered as an index of climatic change for a period of several decades at a latitude (–80^o N) where global models suggest that climate warming should be most pronounced (Kattenberg et al. 1996; cf. also Hardy and Bradley 1996 and, for a recent analysis of the more equivocal observational picture, Rigor et al. 2000). However, these series, all measured within a few kilometres of each other, appear to present conflicting testimony. The mass balance records and the fluctuations of the terminus of White Glacier could be interpreted as suggesting climatic warming whereas the Thompson Glacier terminus record and the Colour Lake ice-cover record might suggest cooling. Our purpose here is to present the measurement records in juxtaposition and to use them to sound a cautionary note about the interpretation of climatic change based on limited evidence.

Basic physical characteristics of the glaciers and the lake are listed in Table 1.

Table 1. Physiographic details.

	Longitude	Latitude	Area (km^2)	Minimum elevation (m)	Maximum elevation (m)
Baby Glacier	–90° 58?	–79° 26?	0.6	715	1175
White Glacier	–90° 34?	–79° 26?	38.7	75	1782
Thompson Glacier	–90° 34?	–79° 26?	270.7	75	1858
	Longitude	**Latitude**	**Area (km^2)**	**Surface elevation (m)**	**Maximum depth (m)**
Colour Lake	–90° 45?	–79° 25?	0.1	176	24

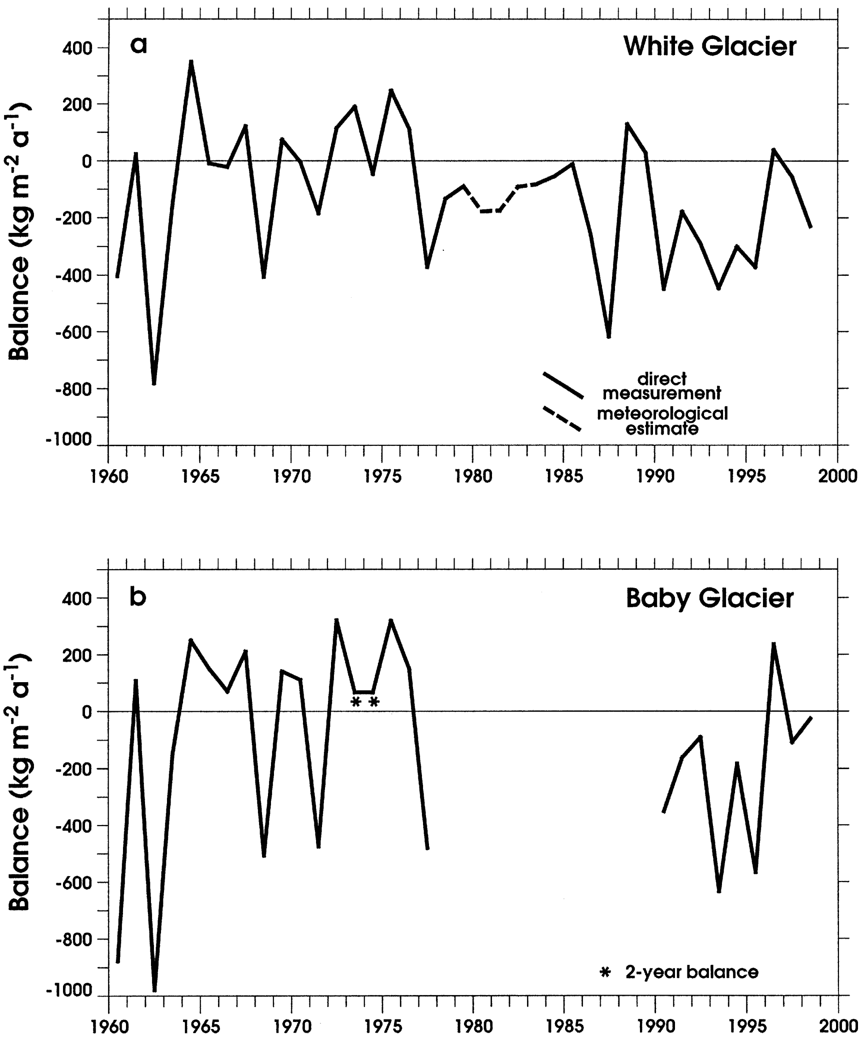

Figure 3. The time series of annual mass balance for White Glacier (1960–1991: Cogley et al. 1995; 1992–1998: from our records) and Baby Glacier (1960–1977: Alean and Müller 1977; 1990–1998: from our records). The meteorological estimates for White Glacier for 1980–1982 are derived using the model of Glenday (1989).

Two glacier mass balance records

The mass balance records of White Glacier and Baby Glacier are shown in Figure 3. These measurements show that losses exceeded gains during the period, so that both glaciers are smaller now than they were when measurements began. Cogley et al. (1996b) reassess the record from White Glacier and show that, when due allowance is made for measurement uncertainty (the magnitude of which is itself quite uncertain), the conclusion that the mass-balance normal is indeed negative is statistically significant. This point is enlarged upon below. For 1960–1991, the mass-balance normal of White Glacier is -100 ± 96 kg m^{-2} a^{-1} with 95% confidence.

Adams et al. (1998) discuss the record from Baby Glacier, which is clearly less complete than that of White Glacier. The two series are nevertheless highly correlated ($r = 0.932$ for 1960–1991), which is to be expected (Cogley and Adams 1998) given their spatial separation of only 10 km. The mass-balance normal of Baby Glacier is -112 ± 182 kg m^{-2} a^{-1}, which is not distinguishable from the global small-glacier average, -136 kg m^{-2} a^{-1}, estimated (with a correction for spatial bias) by Cogley and Adams (1998).

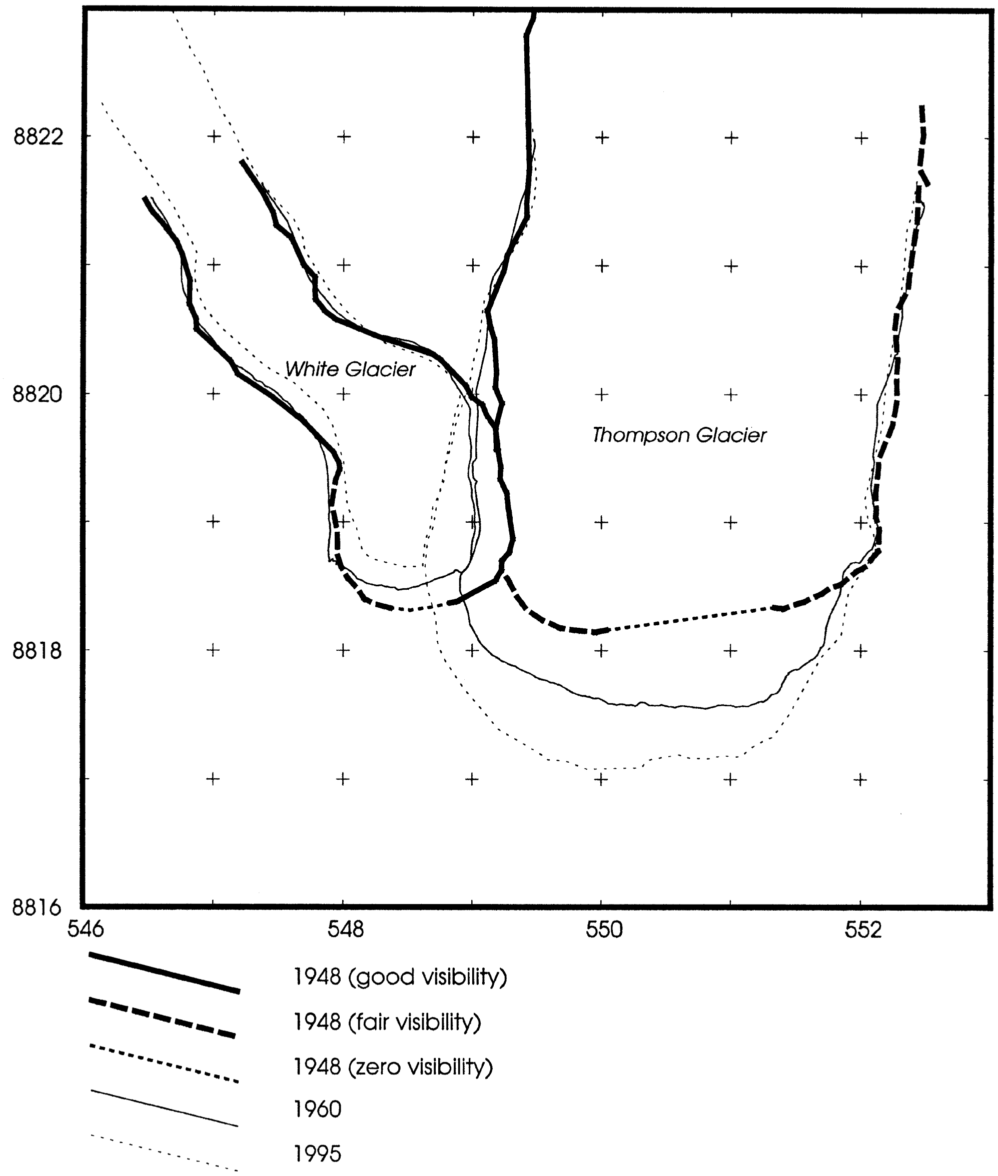

Figure 4. The contiguous terminuses of Thompson Glacier and White Glacier as mapped (National Research Council 1962c) from aerial photography flown on 2 August and 15 August 1960, with positions superimposed from 1948 (dashed line; Cogley and Adams 2000) and 1995 (dotted line; Cogley et al. 1996a).

Fluctuations of two glacier terminuses

Figure 4 shows re-constructions of the positions of the terminuses of White Glacier and Thompson Glacier. The re-constructions extend backwards and forwards in time from the datum of the 1960 positions, which are taken from maps (National Research Council 1962a, b) based on photogrammetry and controlled by detailed ground survey (Haumann 1963). Positions were determined (Cogley et al. 1996a, Cogley and Adams 2000) by digitizing and rectifying outlines from air photographs, including oblique photographs from 1948 (Cogley 1999a), and airborne SAR imagery.

It can be seen that the White Glacier terminus has retreated significantly, which tends at least superficially to reinforce the mass-balance evidence. Thompson Glacier, however, has clearly advanced during the same period, and thus adjacent, impinging glaciers are behaving quite differently.

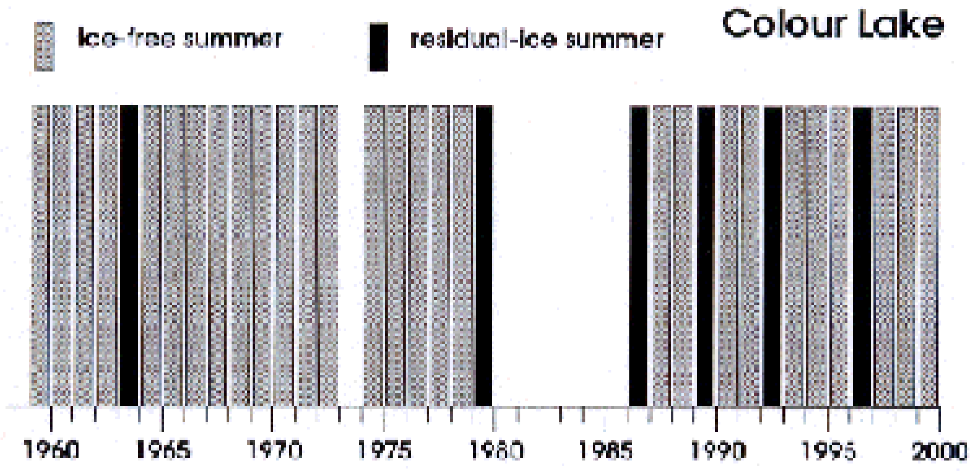

Figure 5. The ice-cover record for Colour Lake, 1959 to 1999 (Doran et al. 1996, and our records). Dates of breakup of the ice cover are known for some years, but not for enough years to extract an informative time series.

The lake "ice-off" record

The ice-off record for Colour Lake (Fig. 5; Doran et al. 1996) is a more basic record than those discussed above. It shows years when Colour Lake became completely ice-free and years when ice persisted through one summer to become part of the ice cover of the following hydrological year. The interesting feature here is the increasing incidence over time of residual-ice summers, which may be summarized as in Table 2.

Although this record is coarsely quantified and thus scarcely amenable to statistical treatment, it does suggest that lake ice covers are becoming more persistent. This, like the advancing terminus of Thompson Glacier, could suggest climatic cooling. Further details and interpretation of the lake ice record are available from Adams et al. (1989) and Doran et al. (1996, 1999).

Table 2. Decadal frequency of residual-ice summers, Colour Lake.

Decade	Number of years with observations	Frequency (percent)
1959–1968	10	10
1969–1978	9	0
1979–1988	4	50
1989–1998	10	30

DISCUSSION

The data presented here raise three questions. First, are these glaciers becoming smaller? Second, is it paradoxical that contiguous glacier terminuses should behave differently? Finally, can a long-term record of breakup of lake ice indicate a climatic shift with adequate confidence?

The average of the annual mass balances of White Glacier shown in Figure 3 is –123 kg m^{-2} a^{-1}, but neither simple visual inspection nor statistical analysis reveal any trend. In fact, Cogley et al. (1996b) show that natural variability and the uncertainty in the measurements combine to make it very unlikely that any climatologically plausible trend could be identified in such a record. Further, it is noteworthy that the sum of the two most negative annual mass balances, –1400 kg m^{-2}, almost offsets the sum, 1550 kg m^{-2}, of the 11 years of positive mass balances, and accounts for almost a third of the net loss of about –4700 kg m^{-2} over the 38 years from 1960 to 1997. (We assume here that the three years without measurements had average annual balances.) Thus extreme years can influence even a three- or four-decade record strongly. This illustrates a point made by Cogley et al. (1995), who found that, under certain plausible assumptions, 25–30 years of record are required before confidence in the conclusion that White Glacier's balance is negative reaches 95%.

Statistically, the mass balance of Baby Glacier is indistinguishable not only from that of White Glacier but also from zero—in other words, from a state of equilibrium. This is a consequence of the record being both shorter and more intrinsically variable than that of White Glacier. The average balance for the full record shown in Figure 3 is –126 kg m^{-2} a^{-1}, but, as for White Glacier, no trend can be identified.

Glaciers respond to climatic change in various ways. For example, they can become thicker or thinner and can contract or expand in area. Monitoring the advance and retreat of glacier terminuses is a well-known and often-used means of indicating glacier change. In Figure 4, the terminus positions of Thompson Glacier, a large glacier (271 km^2) flowing out of the Müller Ice Cap, and White Glacier, a smaller (39 km^2) valley glacier, are shown. The terminus positions over the period 1948–1996 clearly depict the advance of Thompson Glacier and retreat of White Glacier. Table 3, summarizing these rates, indicates that White Glacier has been in retreat throughout the record, with a near-stillstand at around 1970, while over the same period Thompson Glacier advanced but at a steadily decreasing rate.

In fact, it is not difficult to interpret these apparently dissimilar signals. The rationale is the same as an analogy with two ships, a small boat and a large ocean-going liner, each given the order to come to a stop, and then to reverse. The smaller of the two succeeds at this manoeuvre much more quickly. We interpret the dissimilarity as arising because, although White Glacier has responded to the same climatic signals as Thompson Glacier, it completed its response to Neo-glacial (early 19th century) cooling some decades ago and is now exhibiting a response to more recent warming. Thompson Glacier, on the other hand, has yet to slow to a stop in response to Neo-glacial cooling. Jóhannesson et al. (1989), exploring the implications of kinematic-wave theory, presented an expression for the response time of a glacier to climatic forcing,

$$? = -?_i H/b,$$

in which $?_i$ = 900 kg m^{-3} is ice density, H (m) is a typical glacier thickness and b(kg m^{-2} a^{-1}) is the mass balance at the glacier terminus. This expression has become widely used as a convenient summary of the influence of glacier dynamics on glacier-climate interactions. For the glaciers discussed here, it is reasonable to assume that the mass balance at the terminus of Thompson Glacier is the same as that measured on the terminus of White Glacier, of the order of –2000 kg m^{-2} a^{-1}. Typical thicknesses, derived from limited seismic observations, are 200m for White Glacier and 400m for Thompson Glacier; these therefore give response times of 90 years and 180 years respectively. Analysis of the Baby Glacier record (Adams et al. 1998) suggests that it responds to climatic forcing even more quickly than White Glacier. Approximate estimates of H = 20 m, and b = –600 kg m^{-2} a^{-1} yield an estimate of Jóhannesson's ? equal to 30 years for Baby Glacier.

Only two other, less detailed, records of terminus fluctuations are available from Axel Heiberg Island. Müller (1969) documented the behaviour of the terminus of Good Friday Glacier (641 km^2) in southern Axel Heiberg Island. He gave advance-rate estimates of 20 m a^{-1} for 1948–1952, accelerating to 200 m a^{-1} for 1964–1967 and decreasing to <120 m a^{-1} for 1967–1969. McMillan (1998) suggested that Bunde Glacier (25 km^2) in northern Axel Heiberg Island had exhibited practically no change in terminus position between 1955 and 1983. Thus the tiny sample from Axel Heiberg Island (where there are more than 1100 glaciers) consists of four glacier terminuses; of these, two exhibit marked but decelerating advance, one exhibits moderate retreat and one appears to exhibit no change. It is interesting that the advancing glaciers are the larger members of the sample, suggesting that glacier size should be controlled for in such comparisons. Glacier terminus fluctuations are integrated responses to climatic change over a span of past time, the duration of which is in general quite uncertain.

The Colour Lake ice breakup record must be considered with some caution as an indicator of climatic change, as many factors contribute to determining whether the ice cover disappears or not. These factors include summer air temperature, summer solar radiation and/or cloud cover, the nature of the frozen cover that develops on the lake in winter (including the variable but always thin snowpack), differences in the efficiency of mixing of the lake water column between ice-free and ice-covered summers, and the incidence during the spring and summer months of down-glacier winds that promote rapid breakup. Doran et al. (1996) considered each of these, and other, factors, and concluded that the most likely explanation for the apparent increase in frequency of persistent ice covers is that cooler summers make breakup less probable. Sufficiently detailed observational series of local temperatures are not long enough to test this argument rigorously. In short, the record portrayed in Figure 5 is a very simple measure of a complex system, but the increased frequency of multi-year, residual ice may be indicative of cooler (or cloudier, or snowier) conditions, apparently contradicting evidence from other nearby bodies of ice.

Table 3. Advance Rates (m a^{-1}) of White Glacier and Thompson Glacier, 1948 to 1995. One-year intervals from 1959–1960 to 1967–1968 are from ground surveys (Müller 1963, Kälin 1971). Multi-year intervals are from photogrammetric analysis (Cogley et al. 1996b, Cogley and Adams 2000).

Interval	Thompson Glacier	White Glacier
1948–1960	58.5 ± 2.00	–12.6 ± 1.20
1959–1960	26.9 ± 2.40	–1.9 ± 1.40
1960–1961	18.5 ± 2.40	–3.0 ± 1.40
1961–1962	20.9 ± 2.40	–6.1 ± 1.40
1962–1963	26.7 ± 2.40	
1963–1964	16.4 ± 2.40	
1964–1965	13.8 ± 2.40	
1965–1966	18.2 ± 2.40	
1966–1967	26.8 ± 2.40	
1967–1968	12.5 ± 2.40	
1960–1972	19.4 ± 0.63	–5.8 ± 0.38
1972–1977	21.2 ± 1.21	–0.3 ± 0.94
1977–1988	8.1 ± 0.48	–7.4 ± 0.73
1988–1995	7.2 ± 1.13	–9.8 ± 1.70

CONCLUDING REMARKS

The primary aim of this paper is to illustrate why indicators of climatic change, especially generalized indicators, should be interpreted with caution. We have shown and offered interpretations of five data series involving ice. It is probable that if only one of these had been available for analysis, the temptation to over-interpret results would have led to wrong conclusions. Perhaps more significantly, the most easily observed record, and the one most readily replicated over a broader region, is discordant with the indications from the other records.

The terminus records for White Glacier and Thompson Glacier seem to suggest shrinkage and growth respectively, but these differing indications are readily explained by consideration of glacier dynamics and the differing response times of glaciers of differing size. The main problem with records of glacier terminus fluctuations is the temptation to see them as guides to the contemporary or even future climate rather than as integrators of climatic history. Commentators in the popular media regularly succumb to this temptation, and it is not unknown even in the scientific literature.

The most directly climatological (but also most expensive) of these records, the mass-balance records of White Glacier and Baby Glacier, have higher temporal resolution than the terminus records and, for that and other reasons, exhibit greater variability. Both, however, suggest glacier shrinkage, and one of them demonstrates shrinkage with some degree of statistical confidence. The climatological interpretation is therefore that the climate is now warmer and/or less snowy than it was when, at some time in the past, the glaciers grew to their present extents.

The Colour Lake ice breakup record is the anomaly in the set of records assembled here. An increasing frequency of multi-year ice on the lake is thought to be a response to cooler summers. It remains to be seen whether this suggestion can be validated or whether other explanations must be sought or revisited. Possible alternative explanations include warmer winters with a concomitant increase in snow; increased precipitable water due to atmospheric warming and perhaps changes in the large-scale circulation; and a decrease in the effectiveness of katabatic air flows draining from the higher parts of White Glacier and Thompson Glacier. Assuming, however, that there is indeed a climatological signal in the Colour Lake record, it would be well worth finding out how to disentangle it from the limnological and hydrological signals which, for the present purpose, can be regarded as noise. This is because the relevant observation is simple and inexpensive, and because suitable observation sites, namely small lakes, are widespread in the Canadian high Arctic and at high latitudes generally. For example, high-resolution microwave imagery from orbiting satellites such as Radarsat could provide extensive late-summer coverage of such sites in large numbers. Lower-resolution passive-microwave imagery has already been used (e.g., Smith 1998) to estimate a roughly analogous quantity, the duration of summer melting, for sea ice.

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