51ST EASTERN SNOW CONFERENCE
Dearborn, Michigan 1994

The 30-Year Mass Balance of a High Arctic Glacier
Perspectives from the White Glacier, Axel Heiberg Island, NWT, Canada

M.A. ECCLESTONE[1], J.G. COGLEY[1] AND W.P. ADAMS[1]

ABSTRACT

The mass balance of the White Glacier, Axel Heiberg Island, N.W.T., Canada (79°30'N, 90°42'W) has shown no discernible trend toward a more negative balance for the period of record 1960-1991. This concurs with a lack of evidence for climatic warming in the high Arctic. Nevertheless, measurement error associated with stake measurements is large enough to mask climatologically plausible balance trends. The equilibrium-line altitude (ELA) averages 975masl and the accumulation area ratio (AAR) is 0.65. Mass balance is well correlated with ELA. Comparison of the White Glacier mass balance with records of other high Arctic glaciers suggests that the White Glacier is representative of the regional setting. Calculations of the regional balance normal for the high Arctic yield an estimate of the high Arctic contribution to eustatic sea level rise which agree with published values.

INTRODUCTION

The mass balance record of the White Glacier has been reassessed incorporating new data collected since 1983. The result is a glacier mass balance for the period 1960-1991, a record of 30 years. This is one of the longest such records in Canada.

The purpose of this paper is to present the highlights of our analysis and to discuss them briefly, with some emphasis on the errors associated with field measurements. All of the raw data and further analytical material can be found in Cogley *et al.* (1994).

All field measurements were made using standard techniques associated with the stratigraphic system as detailed in Ostrem and Brugman (1991).

SETTING

White Glacier, located on Axel Heiberg Island (Figure 1), is a compound valley glacier, about 15 km long and 38.7km^2 in area (Figure 2a). The tongue is approximately 1km wide and surface elevations range from 1782masl down to 75masl. Ice thickness range from 200m to 400m (Blatter, 1985). Interestingly, White Glacier is polythermal, with a cold outer shell and, a temperate sole in the interior of the tongue (Blatter, 1985, 1987).

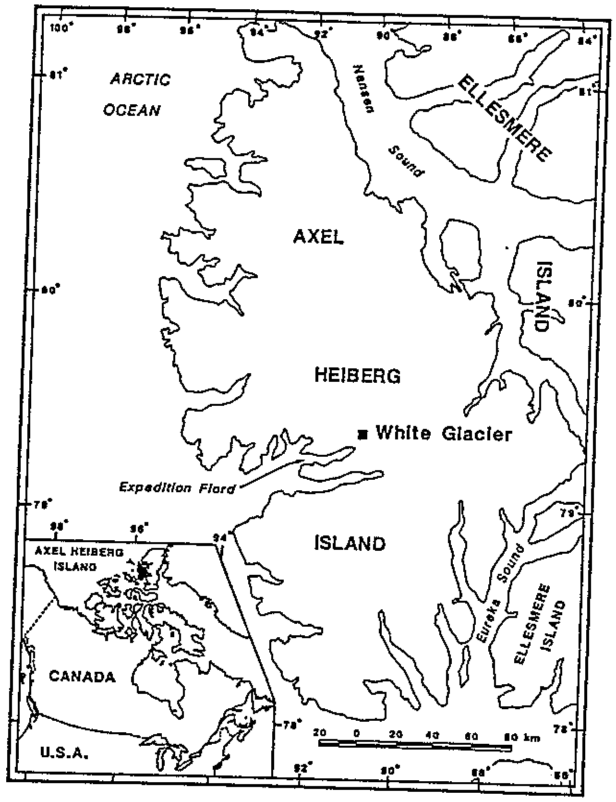

Figure 1. Location of White Glacier

ERRORS ASSOCIATED WITH GLACIER MASS BALANCE

We estimate the error in annual stake mass balances for the White Glacier to be in the order of 200-250mm (i.e. 200-250 kg m^{-2} a^{-1}), due largely to the local non-representativeness or under-sampling of the glacier surface. This problem may be considered on two scales, the local and the glacier-wide. At the local scale (tens to hundreds of metres), glacier

[1]Department of Geography; Trent University; Peterborough, Ontario K9J 7B8 Canada

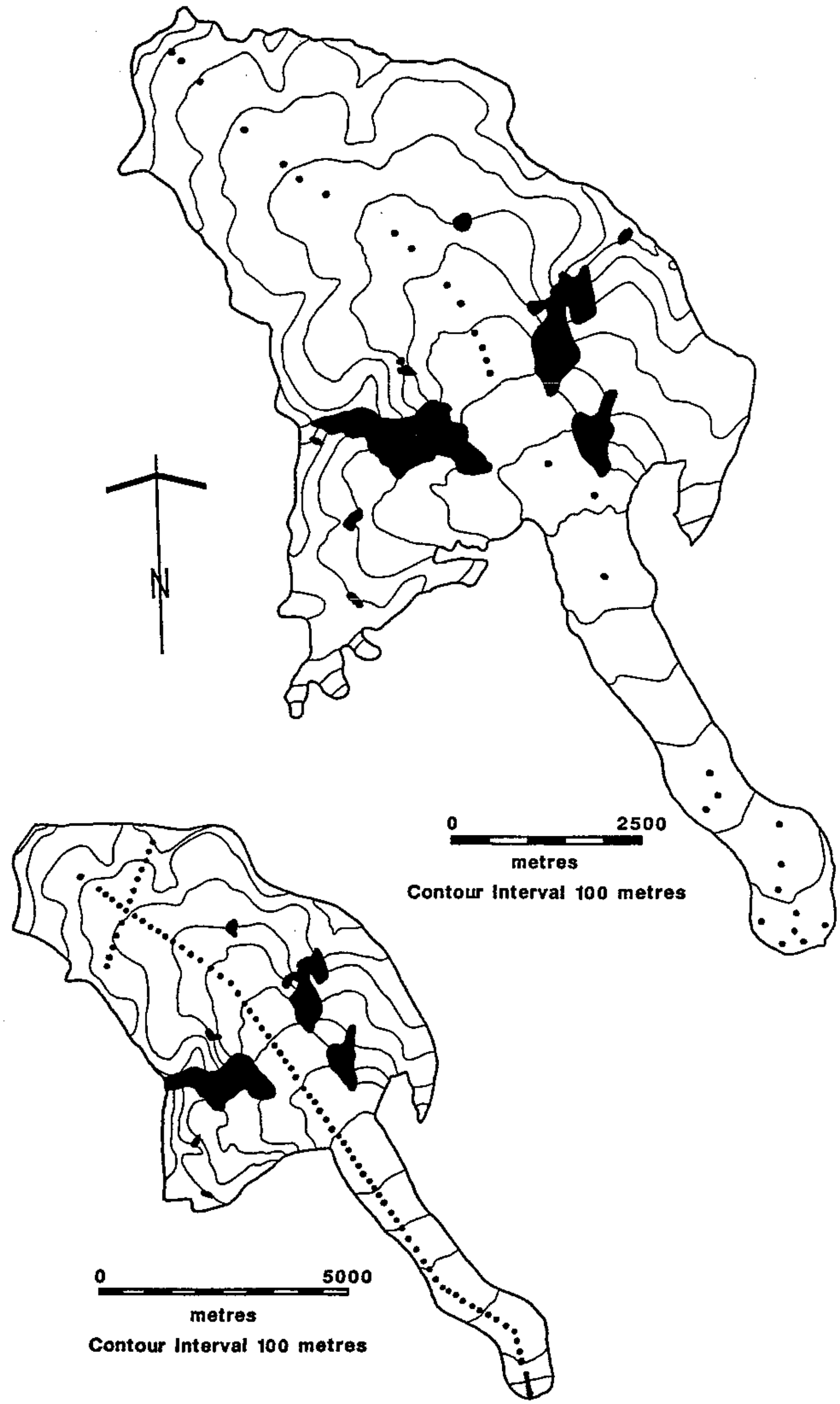

Figure 2a & 2b. The existing stake network on White Glacier and the original network (smaller inset), from the early 1960s.

surfaces have noticeable microtopography which reflect the variations in mass balance and, in fact amplify the spatial variability of mass balance. While individual stake measurements can be quite accurate (Adams, 1966) extrapolation of a single stake value beyond a few metres invariably produces error in mass balance calculations. On a glacier-wide scale, it is impossible to sample inaccessible and dangerous areas which may include large areas especially near the glacier edges. Other researchers (i.e. Lliboutry, 1974; Braithwaite and Olesen (1989)) have modelled stake networks, particularly in the ablation zone and have arrived at results comparable to our estimates.

For the White Glacier, the source of this error is compounded when examining the stake network over time (Figure 2a & 2b). Extrapolating data from fewer and fewer stakes glacier-wide, must create and enhance error. The smaller network now in existence is partially a result of a decreasing field program where the glacier is now visited only once annually, and to a lesser extent because dangerous locations on the glacier are avoided (i.e. the 800-900masl elevational zone is a relatively steep ice-fall with many crevasses). Presently, the White Glacier stake network is more dense in the safer ablation zone (between 2 - 10 km^{-2}) than in the accumulation zone (<0.5 km^{-2}).

Generally, stakes in the ablation zone are drilled below the ice surface to a depth of 4 - 5m. Although these stakes generally melt out of the ice in 1 - 2 years, they remain upright and do not settle into the glacier. Thus, measurements from these stakes are as "good as possible". With a reasonable stake density on the snout, extrapolating over the appropriate glacier area should not produce a large error. Yet, in large melt years stakes frequently "melt out" and increase the error.

Stake measurements in the accumulation zone are more problematic. The stakes are originally anchored in snow that metamorphoses over time. This causes the stake to settle an unknown amount but certainly a few centimetres. Also, as the stake is always above the surface it is subject to harsh conditions (i.e. down-glacier winds) which usually causes the stake to tilt down-glacier. This makes correlating changes in stake measurements from year-to-year and to the previous year's snow surface uncertain and introduces sizeable error. For example, we investigated ten such measurements for 1990 and 1991 and found the standard error was 68mm of snow, or on average about 10 percent of the average of the two depths. A ten percent error in positive values will typically be of the order of 20 - 30mm of water equivalent. When extrapolated over the large accumulation zone areas, it is not surprising that error exists in our annual stake mass balances.

THE MASS BALANCE OF THE WHITE GLACIER, 1960 - 1991

The mass balance record is shown by Figure 3 while Table 1 provides the annual mass balances and associated indices. The balance normal (i.e. the average of the 29 years of record) is -100mm a^{-1}, while the average ELA is 974 masl and the mean AAR is 0.65.

The average ELA agrees with earlier estimates determined by Weiss (1984), which is encouraging, while the AAR is similar to observations of mountain valley glaciers in other parts of the world.

To estimate the uncertainty in the balance normal, we may take as a starting point either the estimate of 200 - 250mm discussed above, or an independent estimate based on the variability in the time series. Mainly because 200 - 250mm is a nominal rather than a formal estimate of the standard error of the individual stake mass balances, it is desirable to choose an independent estimate (standard deviation of the sample divided by the square root of the number of years of record). Thus, the mass balance normal for the White Glacier from 1960 to 1991 is -100 ± 48mm a^{-1}. Since the balance differs from zero by more than two standard errors, we may be 95 percent confident that the balance is negative. Further analysis using autocorrelation confirms that the balance is indeed negative (Cogley *et al.* 1994).

Detecting a trend is, however, more difficult than establishing the sign of the balance normal. Figure 3 shows a relatively noisy record, due to climatic variability and measurement error. We calculated the trend and its standard error from a linear regression of the series of annual mass balances on the time, measured in years since 1960. The result is a trend of -2 ± 5mm a^{-2}. Clearly, we must be able to measure glacier mass balances with about a tenfold greater accuracy before detection of a trend becomes realistically possible. One line of inquiry which does not depend on improved accuracy is to explore how uncertainties evolve as the available record grows. We have stepped through the record one year at a time re-estimating both the balance normal and the balance trend. The result is illustrated in Figure 4, which shows a slow increase, proportional to the root of the number of the years of record, in our confidence in estimates of the balance normal and balance trend. Only after about 25 years can we

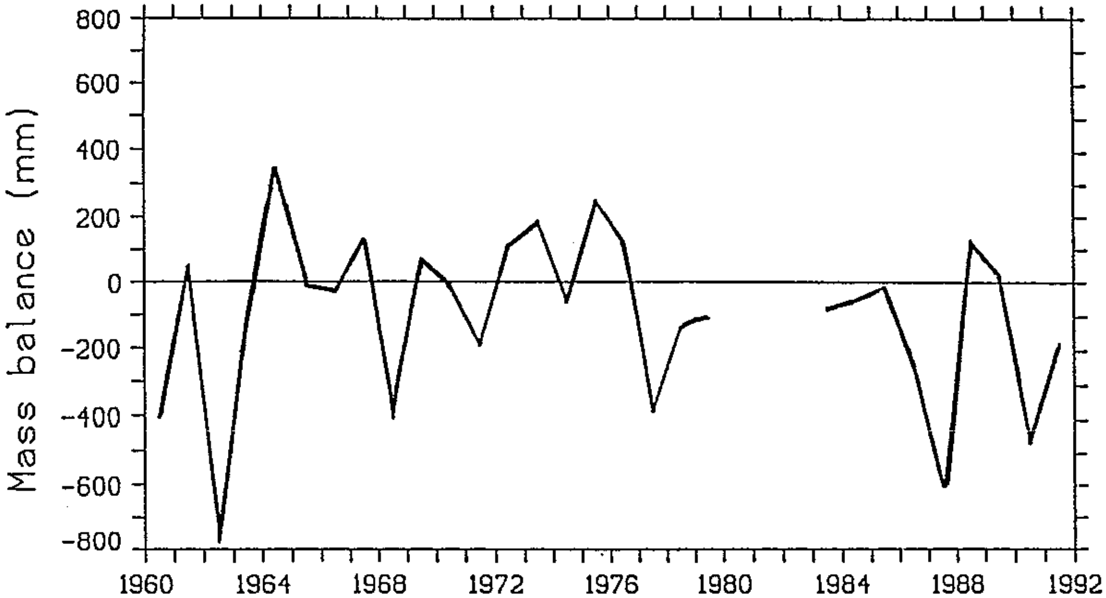

Figure 3. Mass balance series for 1960-91.

Table 1. Mass balance and related properities of White Glacier.

Year	n	B (mm)	h_o (m)	AAR	Year	n	B (mm)	h_o (m)	AAR
1960	71	-404	1261	0.40	1977	76	-372	1093	0.59
1961	85	23	931	0.74	1978	23	-134	1018	0.67
1962	115	-781	1371	0.20	1979	63	-109	1043	0.65
1963	80	-154	1171	0.50	1980				
1964	31	350	480	0.91	1981				
1965	28	-9	886	0.77	1982				
1966	51	-22	996	0.69	1983	26	-83	980	0.71
1967	29	121	828	0.80	1984	27	-55	1009	0.69
1968	50	-406	1225	0.43	1985	28	-12	897	0.76
1969	76	74	908	0.76	1986	33	-259	1072	0.62
1970	68	-4	953	0.73	1987	31	-617	1444	0.09
1971	51	-184	1107	0.59	1988	25	128	470	0.91
1972	91	115	659	0.86	1989	31	28	511	0.90
1973	49	190	746	0.82	1990	27	-448	1395	0.16
1974	48	-46	997	0.69	1991	27	-179	1168	0.50
1975	63	247	800	0.81					
1976	65	112	832	0.80	Avg.	51	-100	974	0.65

n: number of stakes; B: annual whole glacier mass balance; h_o: equilibrium line altitude; AAR: accumulation area ratio

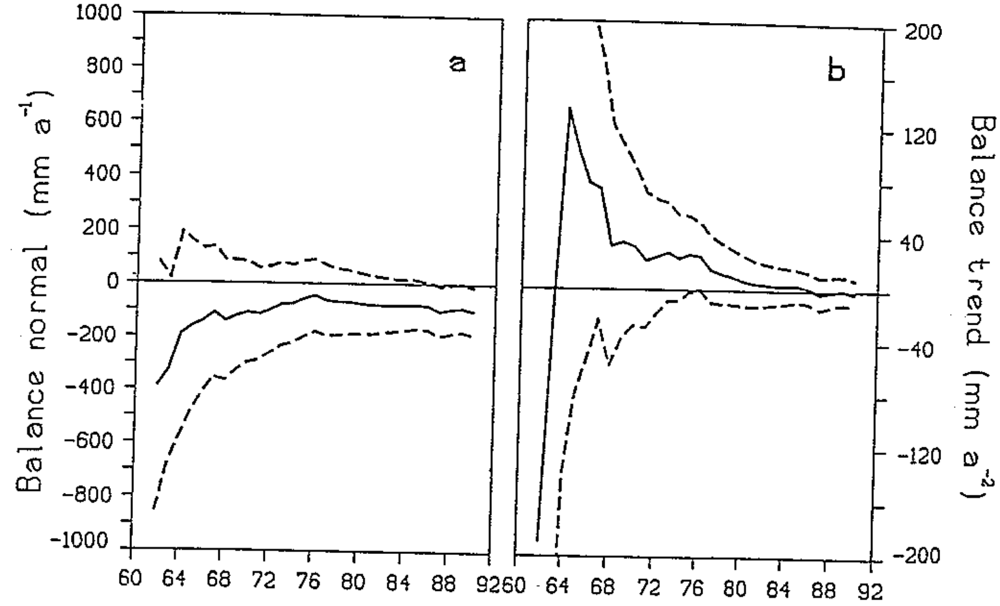

Figure 4. Balance Normal (a) and trend (b) of the White Glacier.

Dashed lines enclose 95 percent confidence regions. Each year the normal, trends and errors are recalculated with the record available to date. The 1980-82 gap in the record was estimated from meteorological estimates from earlier work on the glacier.

claim with 95 percent confidence, that the balance normal is not zero. A much longer record will be needed before we can determine with the same confidence, that the trend is not zero.

COMPARISONS WITH OTHER MASS BALANCE RECORDS

In an attempt to place the balance series of the White Glacier in its regional context, we assembled data from other high arctic glaciers (Table 2). Analysis shows (Cogley *et al.* 1994) that the White Glacier is representative of the Canadian high arctic and that the dispersion of single glaciers about a regional balance normal is not very great, about -82mm ± 50mm a^{-1}.

The relatively noisy mass balance record, along with measurement error makes estimating the contribution to sea level rise difficult. While a review of estimates of sea level rise from the literature (e.g. Warrick and Oerlemans, 1990: Gornitz, 1993; Meier, 1984) range from 1.0 - 2.4mm a^{-1}, the former value is most often cited. Meier (1984) used long-term measurements and estimates of volumetric change, and hydrometeorlogical methods to estimate average mass balances for 1900-1961 in 13 glacierized regions. He found that the global contribution from small glaciers to sea level rise was 0.46 ± 0.26mm a^{-1}.

Using the regional balance from above, and the glacier covered area of the high arctic, (108,600 km^2 - Meier, 1984), we calculate a value for sea level rise of 0.024 ± 0.015mm a^{-1} for the region. Acceptance of this value implies that the high arctic, although it has fully one fifth of the world's small-glacier area, contributes only one twentieth of the estimated net loss of water from small glaciers to the oceans.

CONCLUSIONS

Errors in stake mass balance values are estimated to be of the order of 200 - 250mm on the White Glacier, due to under-sampling and stake measurement errors. Errors in the glacier mass balance are of the same order as above; however, analysis of the time series for the period of record (1960 - 1991) produces an average balance value with a noticeably smaller error (-100 ± 48mm a^{-1}).

To reduce uncertainty in balance estimates, the stake network on the White Glacier requires some

Table 2. Mass balance series for high Arctic glaciers (mm)

Name/ Island	<B> (mm a^{-1})	dB/dt (mm a^{-2})	d (km)	Area (km^2)	Min-max elev (m)	Time span	N_y
White Gl/A.H.I	-100±48	-2 ± 5	0	38.7	53-1782	1960-1991	29
Baby Gl/A.H.I.	-112±91	3 ± 11	10	0.6	715-1175	1960-1991	19
Meighen Gl/Meighen	-129±52	7 ± 5	172	85	70-267	1960-1991	30
Devon IC NW/Devon	-50±23	1 ± 3	505	1696	0-1800	1961-1991	30
South IC/Melville	-29±57	-19±15	730	66	490-715	1963-1974	10
South IC* Melville	-73		730	66	490-715	1974-1980	7
Gilman Gl Ellesmere	-97±47		454	480	410-1850	1957-1960	5
Gilman Gl* Ellesmere	-29		454	480	410-1850	1957-1967	11
Per Ardua Gl/Ellesmere	-320		339	4.7	300-1700	1968	1
Laika IC/Coburg	-630		484	9.8	0-530	1975	1
SPB NE IC Ellesmere	20±54	-8±14	538	7.6	850-900	1972-1983	6
SPB NE IC*/Ellesmere	-130		538	7.6	850-900	1972-1983	11
SPB SW IC Ellesmere	165		538	3.0	740-820	1983	1

<dB>: Glacier Mass Balance Normal
dB/dy: Glacier Balance Trend
* : Multi-year balance
d: Distance from White Glacier
N_y: Number of years of record
SPB: St. Patrick Bay
A.H.I.: Axel Heiberg Island

changes. Ideally a dense and continuous longitudinal profile should be reestablished (Figure 2b). There is little chance of this occurring, so it is important to emphasize the large errors attached to our estimates, errors which are likely typical of many other mass balance programmes.

Comparisons show that the White Glacier is representative of the Canadian high arctic, and that the dispersion of single glaciers about a regional balance normal of about -80mm a^{-1} is not large.

Evidence for trends is at best inconclusive; present methods of balance measurement are inadequate for detecting trends of the magnitude to be expected in the high arctic. Research on more accurate means of estimating mass balance, therefore, deserves high priority. Such methods which would measure volumetric changes directly, could include using the Global Positioning System and, remote sensing of glacier surfaces at radar wavelengths. At best these methods are in the early stages of development.

Lastly, the regional normal for the high arctic implies a contribution of 0.024 ± 0.015mm a^{-1} to the observe eustatic rise in sea level, which concurs with the standard published estimate of 0.019 mm a^{-1}.

ACKNOWLEDGEMENTS

We gratefully acknowledge the work of all those who have made or assisted with the mass balance measurements of the White Glacier from 1960 through 1991 - they are too many to mention. We thank the following organizations: Polar Continental Shelf Project, Energy Mines and Resources Canada; National Hydrology Research Institute, Environment Canada, Saskatoon; Trent and McGill Universities and Geographisches Institut, ETH, Zurich. Dr. R.M. Koerner made many valuable comments throughout our analysis and earlier drafts of this work. M. Miller and S. Gardiner were of great help in readying this manuscript.

SELECTED REFERENCES

Adams, W.P., 1966. Ablation and run-off on the White Glacier, Axel Heiberg Island, Canadian arctic archipelago, *Glaciology No. 1, Axel Heiberg Island Research Reports*. McGill Univ., Montreal, 77p.

Blatter, H., 1985. On the thermal regime of arctic glaciers: a study of the White Glacier, Axel Heiberg Island, and the Laika Glacier, Cobourg Island, Canadian arctic archipelago, *Glaciology No. 6, Axel Heiberg Island Research Reports,* McGill Univ., Montreal, 107p.

Blatter, H., 1987. On the thermal regime of an arctic valley glacier: a study of White Glacier, Axel Heiberg Island, N.W.T., Canada, *J. Glacio.*, 33, 200-211.

Braithwaite, R.J., O.B. Olesin, 1989. Detection of climate signal by inter-stake correlations on annual ablation data Qamanarssup sermia, West Greenland, *J. Glacio.*, 35, 253-259.

Cogley, J.G., W.P. Adams, M.A. Ecclestone, F. Jung-Rothenhausler and C.S.L. Ommanney, 1994. Mass balance of Axel Heiberg Island glaciers, 1960-1991: A reassessment and discussion. *N.H.R.I. Sci. Rept. 6,* Natl. Hydrol. Res. Inst., Envir. Canada, Saskatoon, xxxp.

Gornitz, V., 1993. Mean sea level changes in the recent past, in Warrick, R.E., E.M. Brown and T.M.L. Wigley, eds. *Climate and sea level change: observations, projections and implications,* Cambridge Univ. P., Cambridge, 25-44.

Lliboutry, L., 1974. Multivariate statistical analysis of glacier annual balances, *J. Glacio.*, 13, 371-392.

Meier, M.F., 1984. Contributions of small glaciers to global sea level, *Science,* 226, 1418-1421.

Ostrem, G., M. Brugman, 1991. Glacier mass balance measurements: a manual for field and office work. *N.H.R.I. Sci. Rept. 4,* Norwegian Water Resources and Electricity Board, Oslo and Natl. Hydrol. Res. Inst., Envir. Canada, Saskatoon, 224p.

Warrick, R.A., J. Oerlemans, 1990. Sea level rise in, Houghton, J.T., G.J. Jenkins and J.J. Ephraums, eds., *Climate change: the IPCC scientific assessment,* Cambridge Univ. P., Cambridge, 257-281.

Weiss, 1984. Massenhaushalt eines gletschers: fragen an glaziologische untersuchungen und die resultate de messreihe am White Glacier in der kanadischen Arktis, *Diplomarbeit,* Eidgenoss. Tech. Hochsch., Zurich, 149p.