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The Impact of Sampling Density on Glacier Mass Balance Determination

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ABSTRACT

To assess the impact of sampling density on determination of a glacier's annual mass balance, we used varying densities of measurement to determine annual mass balance on Columbia Glacier, Washington, and Lemon Creek Glacier, Alaska. The density of the mass balance network ranged from 1 point/km^2 to an absurdly dense 375 points/km^2. The results on both glaciers indicate significant improvement in accuracy resulting from increasing the total number of measurements from 10 to 40 points. The accuracy only slightly improved from increasing the total number of measurements from 40 to 300$^+$ sites. There was not a significant improvement in accuracy on the smaller Columbia Glacier for utilizing more than 100 points/km^2. On Lemon Creek Glacier there was little improvement in mass balance assessment for a network greater than 10 points/km^2.

Key Words: Glacier, Mass balance, Sampling density

INTRODUCTION

The annual mass balance of a glacier is the most sensitive climatic measure of a glacier (IPCC, 1996). Annual mass balance is typically assessed from a sparse network (0.5–50 points/km^2) of sample locations that are not uniformly distributed across the glacier. The main source of error in mass balance measurement programs arises from the non-representativeness of this sparse measurement network from which the whole glacier estimate is determined (Cogley, 1996; Paterson, 1994).

Ideally a mass balance measurement network is scattered uniformly over the entire glacier with a density of measurements sufficient for statistical testing of the results. Logistically measurements are made at only a limited number of points and some areas of glaciers are too crevassed or steep to measure. Consequently, the resulting sparse network generates the question, how many points is enough and how well do the measurement points represent the area around them?

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Table 1. The number of measurement sites used and their density in km² in mass balance studies on selected glaciers: In Switzerland (A) (Herren, Hoelze, and Maisch, 1999), by the Canadian Inland Water Directorate (C) (Ostrem and Stanley, 1969) by the United States Geological Survey (UW) (Krimmel, 1998) (UA) (March and Trabant, 1995), by the Norges Vassdrags–Elektrissen (N) (Ostrem et al. 1980), and by the North Cascade Glacier Climate Project (P) (Pelto, 1996).

Glacier	Ablation Area		Accumulation Area		
	Sites	Density	Sites	Density	Source
Limmern	12	8	17	2	A
Silveretta	4	4	4	2	A
Greis	5	2	5	2	A
Place	30	11	34	20	C
Gulkana	2	.5	3	.3	UW
South Cascade	5	5	5	5	UA
Wolverine	5	1	105	6	UA
Alfotbreen	5	4	126	35	N
Austre Memurubre	8	3	316	52	N
Grasubreen	9	8	110	40	N
Hellstugubreen	13	7	125	25	N
Nigardsbreen	10	4	237	5	N
Vestre Memurubre	6	4	88	10	N
Columbia	3	10	165	250	P
Daniels	4	12	115	280	P
Foss	3	15	110	240	P
Lower Curtis	3	10	185	280	P
Lynch	3	10	125	250	P
Rainbow	3	6	200	180	P

The typical density and total number of measurements currently used in annual mass balance measurement is indicated in Table 1. Measurement densities are usually below 10 points/km^2, hence each point is assumed to accurately represent an area of 100,000 m^2. Mean densities are higher in the accumulation zone 16 points/km^2, than in the ablation zone 5 points/km^2. The North Cascade Glacier Climate Project (NCGCP) utilizes the highest density of measurements 240 points/km^2 in the accumulation zone and 10 points/km^2 in the ablation zone.

Determining the most efficient sampling pattern and identifying the overall accuracy of the sampling network is key to assessing error in annual mass balance measurement. Lliboutry (1974) and Cogley et al. (1996 and 1999) have approached this problem from a statistical standpoint and found that the number of measurement points can be fairly low, but that the overall pattern of mass balance must be known. In this study we approach the issue of errors resulting from measurement networks of varying densities from a purely field measurement perspective. Cogley (1999) pointed out that with a measurement network spaced at 50–100 m apart, the largest source of uncertainty is the error in actual point measurement (> 0.05 m), and sampling error is negligible. Cogley (1999) referred to this method as *reductio ad absurdum*.

This is precisely the method we used on Columbia Glacier in the North Cascades, Washington, and Lemon Creek Glacier Juneau Icefield, Alaska. Both glaciers have a long annual mass balance record (Pelto, 1996; Miller and Pelto, 1999). We compared the mass balance results from an absurdly dense network of measurements to variously sparse networks to determine the error resulting from using increasingly sparse networks.

GLACIER CHARACTERISTICS

Columbia Glacier

Columbia Glacier is a south-facing cirque glacier with a comparatively low slope for a small alpine glacier (0.15). The glacier has the lowest mean elevation (1600 m) of any glacier over 0.5km^2 in the North Cascades. In 1999 Columbia Glacier had an area of 0.87km^2. This low mean elevation despite its southern exposure is due to the tremendous avalanching of the 800-m-high cirque walls on the east and west sides of the glacier and the radiational shading the cirque walls provide (Fig. 1) (Pelto, 1996).

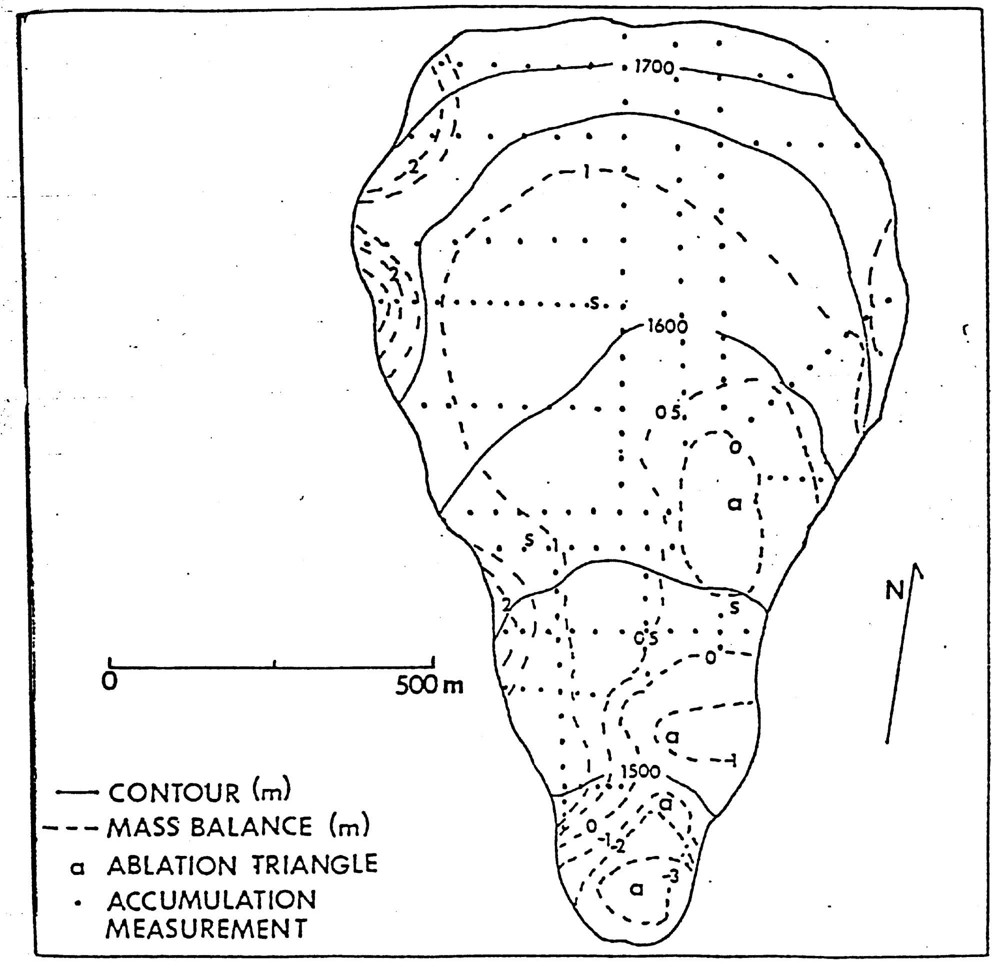

Figure 1. Mass balance map of Columbia Glacier.

The North Cascade Glacier Climate Project has measured the mean annual balance of Columbia Glacier since 1984, using 169 point measurements each year (Fig. 2). The mean annual balance of Columbia Glacier from 1984 to 1998 is –0.44 m/a, –6.55 m for the entire period (Fig. 3) (Pelto, 1996). This is a substantial loss for a glacier that averages less than 75 m in thickness. The resultant glacier thinning, particularly pronounced near the terminus, has caused extensive glacier retreat. The glacier has retreated continuously during this century, –85 m since 1979.

Lemon Creek Glacier

In 1998, Lemon Creek Glacier was 5.6 km long and had an area of 11.8 km^2 (Marcus et al., 1995). From the head of the glacier at 1300 m to the mean Equilibrium Line Altitude (ELA) at 1050–1100 m the glacier flows northward. In the ablation zone the glacier turns westward, terminating at 600 m. The glacier can be divided into four sections: 1) Steep peripheral northern and western margins draining into the main valley portion of the glacier; 2) A low slope (4°) upper accumulation zone from 1220 m to 1050 m; 3) A steeper section (6°) in the ablation zone as the glacier turns west from 1050 to 850 m; 4) An icefall (18°) leading to the two-fingered terminus at 600 m.

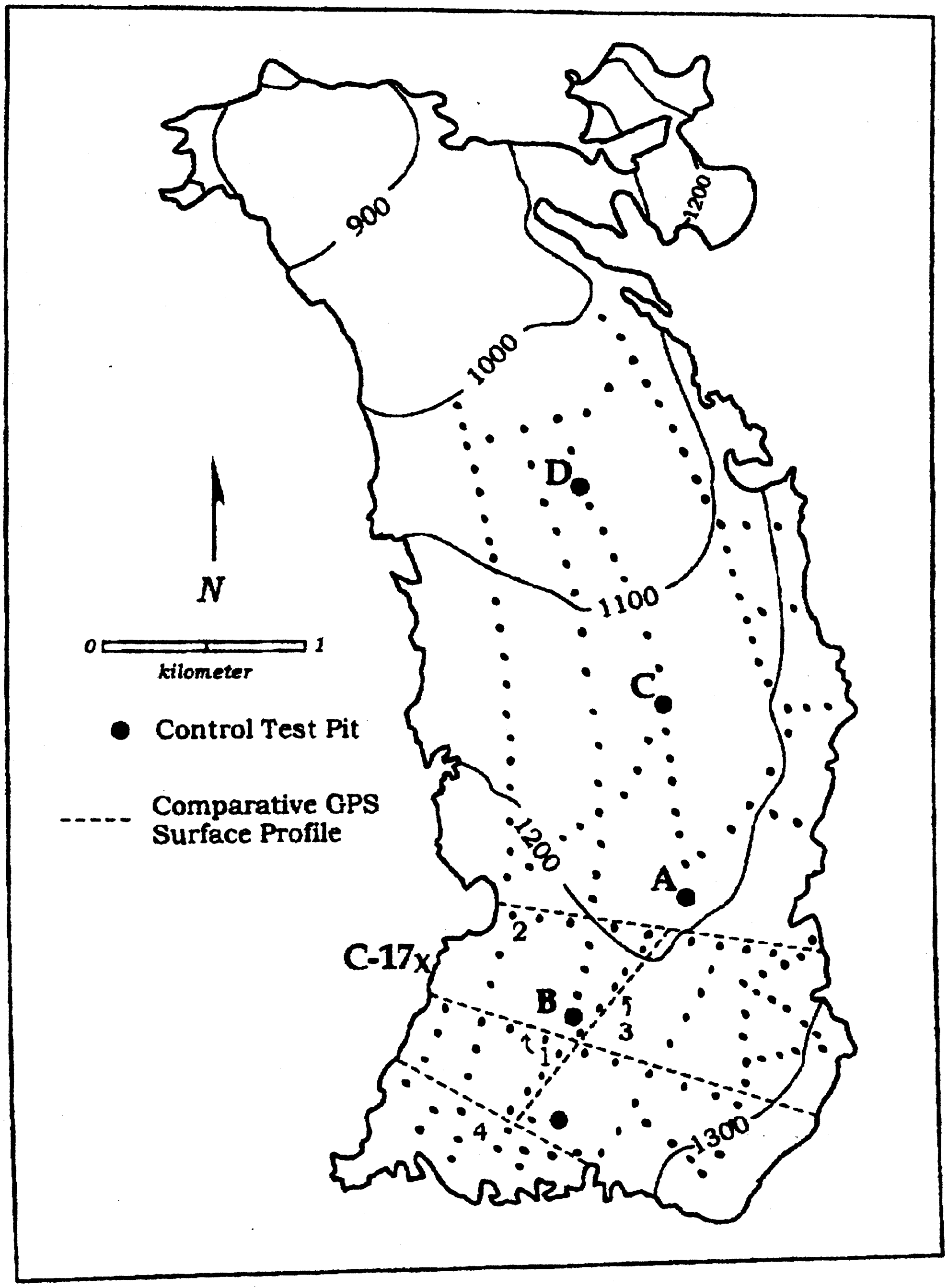

Figure 2. Mass balance map of the Lemon Creek Glacier.

Annual balance on the Lemon Creek Glacier is determined from a network of 8–30 points (Miller and Pelto, 1999). The Lemon Creek Glacier annual balance record indicates that from 1957 to 1976 mass balance loss was –0.23 m/a and thinning was modest on the upper reaches of the glacier (Miller and Pelto, 1999). Despite a higher mean elevation and a higher terminus elevation due to glacier retreat, mean annual balance has been increasingly negative since 1977, averaging –0.78 m/a. The record is particularly negative since 1990, –1.04 m/a (Fig. 3). This negative mass balance has fueled a terminal retreat of 800 m during the 1953–1998 period.

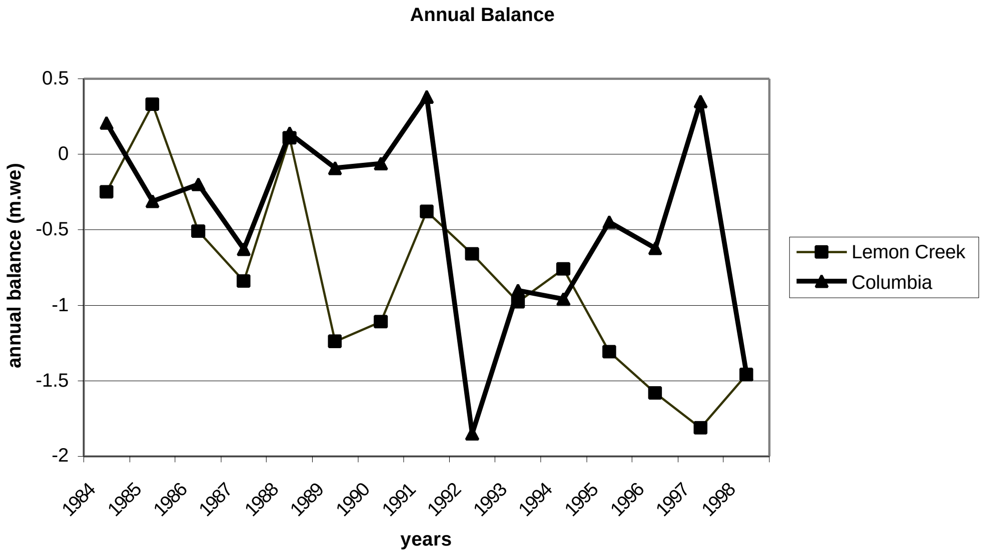

Figure 3. The annual balance of Columbia and Lemon Creek Glacier Alaska in meters of water equivalent.

FIELD MEASUREMENT METHODS

On Columbia Glacier in the North Cascades, Washington, and Lemon Creek Glacier, Juneau Icefield, Alaska, we determined annual mass balance from measurement networks of varying density from a typical low density mass balance measurement network of 1 point/km^2 on Lemon Creek Glacier and 10 points/km^{2}on Columbia Glacier, to an unusually high density of measurements 30 points/km^2 on Lemon Creek Glacier and 375 points/km^2 on Columbia Glacier. Each network is spatially fixed with respect to the adjacent bedrock edges of the glacier and using differential GPS where necessary. Mass balance is measured at the same point, using the same methods at the same time of the year on each glacier. On Columbia Glacier the measurements were completed on August 1 or 2 each year from 1984 to 1998. On Lemon Creek Glacier measurements were completed in July of 1984 and 1998. The resultant mass balance reported here is not the actual annual balance reported for each glacier and determined at the end of the hydrologic year (October 1), but simply the specific mass balance of that date. These dates were utilized because this is the time period when we have the available resources to complete the unusually dense measurement network.

Accumulation zone

The average density of measurements in the accumulation zone used in assessing the mass balance in the accumulation zone of Canadian, Norwegian, Swiss, and United States glaciers is 16 points/km^2 (Pelto, 1996). On Columbia Glacier the typical density used in the mass balance measurements is 180 points/km^2, an unusually dense network. On Lemon Creek Glacier the density ranges from 1 to 4 points/km^2 (Miler and Pelto, 1999). In this study the dense network on Columbia Glacier is 360 points/km^2 and on Lemon Creek Glacier 100 points/km^2. The mass balance measurement network covers a glacier's entire accumulation zone with a consistent distribution of measurements (Fig. 2).

Measurement of accumulation in the accumulation area was accomplished using probing and crevasse stratigraphy. Probing has proved both successful and easy to use in most temperate and subpolar climate settings (Ostrem and Bruggman, 1991). In the North Cascades and Juneau Icefield, all summers are notably warm, resulting in a 2- to 5-cm-thick band of continuous readily identifiable dirty firn that resists penetration. Since North Cascade glaciers rarely have ice lenses, an indicator of little internal accumulation, probing is an accurate method of measuring accumulation layer thickness. The probe is driven through the snowpack until the previous ablation surface is reached. On the Juneau Icefield ice lenses are more common but are discontinuous, and thus repeat measurements are often required to verify that the previous annual layer has been reached. Crevasse stratigraphic measurements were conducted only in vertically walled crevasses with distinguishable annual layer dirt bands. Most of the vertically walled crevasses also tend to be narrow (less than 1 m across). The accuracy of crevasse stratigraphy and probing measurements are cross-checked at a minimum of 25% of the measurement sites by probing between crevasses. This cross-checking identifies measurement points that either represent an ice lens and not the previous summer surface in the case of probing, or areas where crevasses do not yield representative accumulation depth in the case of crevasse stratigraphy. The standard deviation in snow depth obtained in cross-checking and duplicate measurements are smallest for crevasse stratigraphy, ±0.02 m, and ±0.03 m for probing. The narrow range of deviation in vertically walled crevasses indicates that they do yield consistent and representative accumulation depths late in the summer.

Crevasses have generally been avoided in mass balance measurements because of the dangers they present, despite the ease with which the annual layer can be measured. Meier and others (1997) questioned the accuracy of crevasse stratigraphic measurements. Probing, coring, and snowpits are artificial incisions into the glacier to identify the annual layer. There is no reason that a natural incision provided by a vertically walled crevasse, which intersects the same annual layer, would be any less reliable (Pelto, 1997). In fact, in extensive NCGCP tests (Pelto, 1996), crevasse measurements had a lower standard measurement error in duplicate measurements. This is expected given the two-dimensional view of crevasse stratigraphy versus a single dimension in snowpits and probing. In ice sheet areas distant from a dust source this may be difficult, but on alpine glaciers mountaineers and glaciologists have long noticed the ubiquitous nature of these layers (Post and LaChapelle, 1962).

In the North Cascades and Olympics, Washington, at the end of the summer snowpack density of the most recent winter's retained accumulation is remarkably consistent (Pelto, 1996; Krimmel, 1998). NCGCP completed more than 100 snowpits from 1984 to 1986; the range in mean accumulation-layer density for a single glacier was 0.59–0.63 Mg/m^3. Of equal importance was that the range of density variation is of the same order as the density measurement error, determined through repeat measurements. Thus, density measurements are no longer completed during crevasse stratigraphy or probing. As is the case on South Cascasde Glacier (Krimmel, 1998) the mean density used in our calculations of mass balance is 0.60 Mg/m^3. NCGCP routinely measured the snow density using a SIPRE corer at several location on each glacier each year, but has to this date found no deviation from the above noted range. Density must be measured for winter balance assessment in the North Cascades as April and May snowpack measurements show a significant range in density, which changes with time.

On Lemon Creek Glacier density was measured in a continuous profile through the snowpack during the measurement program at three locations. The snowpack density is noted for its consistency, ranging from 0.54 to 0.56 in July, from year to year and place to place (LaChapelle, 1954; Miller and Pelto, 1999).

Ablation measurements

In the ablation zone wooden stakes were emplaced in a sequence from areas that lose their snowcover early in the summer to those that lose it late in the summer and not at all. Ablation stakes were white wooden poles 3.3 m long. This length was chosen as longer stakes are too cumbersome to transport and emplace, and shorter stakes tend to melt out. Ablation measurements were made at a minimum of six stakes on each glacier. Measurements were made in late July and early August on Columbia Glacier, recording the ablation during the first three months of the ablation season, for water resource assessment purposes and redrilling of the stakes when necessary. Ablation measurements were repeated in late September at the designated conclusion of the hydrologic year to determine total annual ablation. On Lemon Creek Glacier ablation measurements are completed each year in July. In this study the observed ablation in July on

Lemon Creek Glacier represents ablation since the previous July. On Columbia Glacier the observed ablation in early August reflects the ablation since the redrilling in early August of the previous summer.

RESULTS

We had the advantage of already understanding the overall mass balance pattern of each glacier in selecting measurement networks that would provide the most representative coverage for the glacier given the total number of measurements in each sample (Pelto, 1996; Miller and Pelto, 1999). Each measurement was assumed to represent the glacier area surrounding that site. Each measurement location for 10, 20, and 40 measurement point networks was specifically selected as the best representative of the average mass balance of the surrounding region. This decision is base on the existing detailed mass balance maps for each glacier. This allowed calculation of the mass balance for each measurement network simply from the mean of all the observations, without biasing the results according to the representativeness of the specific sites.

On Columbia Glacier we used a measurement network with a maximum density of 375 points/ km^2, and a maximum spacing between point of 90 m and a mean spacing of 45 m. Annual mass balance (1984–1998) was typically determined on Columbia Glacier from a measurement network with a spacing of 187 points/km^2 (Pelto, 1996), and a mean spacing of 50 m. On Columbia Glacier using 10 measurement points yielded an error of –0.15 m/a, ranging from –0.07m/a to –0.24 m/a. For a network of 23 points/km^2, 20 points, a consistent error of –0.05 to –0.10 m/a resulted (Table 2). This density of measurement provides an adequate measurement network to determine annual mass balance with an error of –0.10 m/a. The error resulting from the use of 20 measurement points is significant versus using either 169 or 338 points (46–100 points/ km^2) measurement points; however, the consistency of the error suggests even greater accuracy was possible if the overall glacier balance distribution has been determined at some time using a denser measurement network (Fig. 4).

Table 2. The annual balance in meters of water equivalent determined from field measurements of varying density on Columbia Glacier. The fewer the number of measurements, the more negative the annual balance calculated.

Year	10 points	20 points	40 points	84 points	169 points	338 points
1988	0.46 m	0.46 m	0.51 m	0.51 m	0.58 m	
1989	0.39	0.4	0.42	0.41	0.48	
1990	0.41	0.42	0.44	0.43	0.5	
1991	0.84	0.84	0.86	0.85	0.91	
1992	–0.28	–0.13	–0.11	–0.13	–0.04	
1993	–0.08	–0.01	0.01	0.01	0.07	
1994	–0.06	0	0.02	0.01	0.08	
1995	0.08	0.13	0.17	0.14	0.21	
1996	0.05	0.09	0.12	0.1	0.17	0.19 m
1997	0.77	0.81	0.84	0.83	0.92	0.91
1998	–0.23	–0.1	–0.09	–0.11	–0.01	–0.01

There is no significant change in annual mass balance for measurement densities of 40–80 points/ km^2 (46–100 points) compared to 25 points/km^2 (20 points). There is a consistent change in mass balance when either 169 (194 points/ km^2) or 338 (388 points/ km^2) measurement points are utilized, in comparison to the smaller measurement densities. The difference in calculated annual balance ranges from –0.06 to 0.10 m/a. The lower measurement densities consistently underestimate annual balance. There is no significant difference between the mass balance observed at 169 versus 338 locations. To reduce the error further requires utilizing an extensive measurement network in excess of 100 points/ km^2 and possibly as high as 187 points km^2.

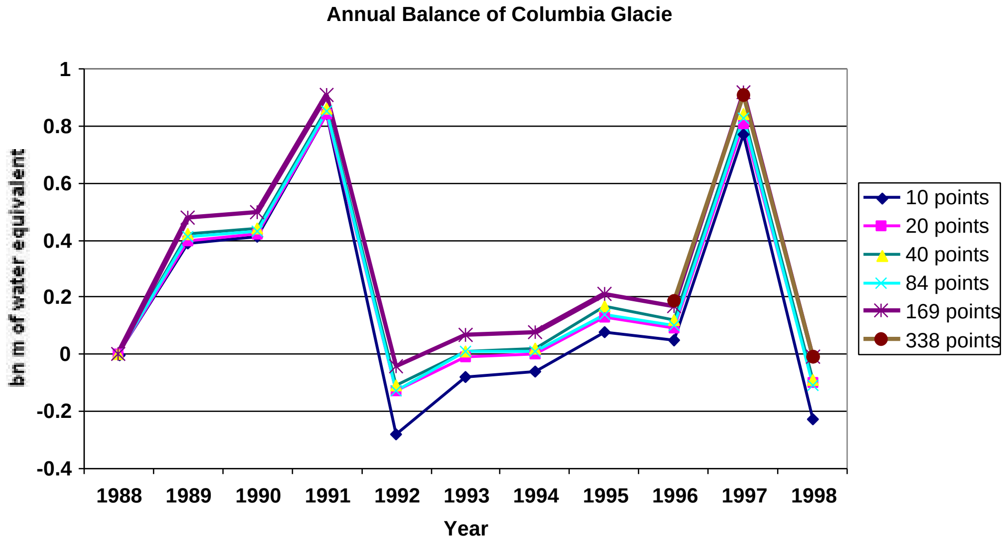

Figure 4. Annual balance of Columbia Glacier.

On Lemon Creek Glacier we have used a measurement network with a maximum density of 30 points/km^2. The mass balance determined from a density of 10 and 20 measurement sites is significantly in error; unlike on Columbia Glacier this error is not consistently negative, instead it is rather random (Table 3). A measurement network of 10 points or 1 point/ km^2 yielded an error of ±0.15 m/a, ranging from –0.07m/a to –0.24 m/a. Using a network of 20 points yielded an error of ±0.10 m/a in annual balance for a measurement network of greater than 2 points/ km^2. The mass balance determined from a network of 40 to 320 observation sites yielded no significant difference in observed annual balance. Thus, on Lemon Creek Glacier a density of 4 points/km^2 was adequate for annual mass balance determination.

Table 3. The observed annual balance on Lemon Creek Glacier determined from field measurements of varying density in meters of water equivalent.

Year	10 points	20 points	40 points	160 points	320 points
1984	0.38 m	0.32 m	0.23 m	0.24 m	0.24 m
1998	–1.31 m	–1.24 m	–1.18 m	–1.16 m	–1.15 m

The variation from mass balance between any two adjacent sites on Lemon Creek Glacier was low, a mean of ±0.07 m compared to that of Columbia Glacier, ±0.35 m. This greater variation despite the fact that the mean spacing of the sites was less on Columbia Glacier, 50 m than on Lemon Creek Glacier, 175 m. Thus, the necessary measurement density necessary to yield reasonably accurate mass balance values was lower for Lemon Creek Glacier. The sheer size of the glacier caused the total required measurements to be similar to achieve reasonable accuracy. This is an expected result given that the majority of the Lemon Creek Glacier shares much more homogenous topographic characteristics compared to Columbia Glacier.

In order to achieve optimal accuracy it is apparent that multiple measurements are needed in each specific mass balance zone of the glacier. If a glacier has large homogenous areas, this reduces the measurement density (Lemon Creek Glacier); if it has many small unique mass balance zones, a higher measurement density is required (Columbia Glacier).

CONCLUSIONS

Detailed mapping of mass balance variations, across the glacier determined from a high-density measurement network over several years, optimizes the annual balance of a glacier from a sparse network of observations. Given that this has been accomplished on a small alpine glacier such as the Columbia Glacier, a measurement density of 20 points/km^2 yielded accurate results. On the larger Lemon Creek Glacier the measurement density needed to achieve reasonable accuracy was 4 points/km^2. In both cases the total number of measurements necessary to achieve consistent accuracy within ±0.10 was 40 points. Statistical tests can be applied to compensate for lower measurement densities however this always entails assumptions. The aim of this study was to illustrate the minimum number of measurements needed to determine annual mass balance accurately from field measurements alone.

REFERENCES

Cogley, J.G. 1999. Effective sample size for glacier mass balance. *Geogr. Ann.*, 81: 79–86.

Cogley, J.G., Adams. W.P., Ecclestone, M.A., Jung–Rothenhausler, F., and Ommaney, C.S.L. 1996. Mass balance of White Glacier, Axel Heiberg Island N.W.T., Canada, 1960–1991. *J of Glaciol*., 42: 548–563.

Fountain, A., Trabant, D., Bruggman, M., Ommaney, C., and Monroe, D., 1991. Glacier mass balance standards. *EOS*, 72(46): 511–514.

Herren, mE.R., Hoelzle, M., and Maisch, M. 1999. The Swiss Glaciers 1995/96 and 1996/97. *Swiss Academy of Sciences, Glaciological Commission, Glaciological Report no. 117-118*.

IPCC, 1996. Climate Change 1995: Contributions of working group I to the second assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Krimmel, R.M. 1998. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1997 Balance Year. *USGS WRI-98-4090*.

LaChapelle, E. 1954. Snow Studies on the Juneau Icefield. *Am. Geogr. Soc., Juneau Icefield Research Project,* Report no. 9.

Lliboutry, L. 1974. Multivariate statistical analysis of glacier annual balances*. J Glaciol.,* 13: 371–392.

March, R.S., and Trabant D.C. 1995. Mass balance, Meteorological, Ice Motion, Surface Altitude and Runoff Data at Gulkana Glacier, Alaska, 1992 Balance Year. *USGS WRI-95-4277*.

Marcus, M.G., Chambers, F.B., Miller, M.M., and Lang, M., 1995: Recent trends in the Lemon Creek Glacier, Alaska. *Phys. Geogr*., 16(2): 150–161.

Meier, M.F, Armstrong, R.A., and Dyugerov, M.B. 1997: Comments on "Annual net balance of North Cascade glaciers 1984–1994" by Mauri S. Pelto. *J of Glaciol*., 43(143): 192–193.

Miller, M.M., and Pelto M.S. 1999. Mass balance measurements on the Lemon Creek Glacier, Juneau Icefield, Alaska 1953–1998. *Geogr. Ann*., 81: 671–681.

Ostrem, G., and Bruggman, M. 1991: *Glacier Mass-Balance Measurements. Canadian NHRI Science Rep.* no. 4.

Paterson, W.S.B. 1994. *The Physics of Glaciers, 3rd Ed*. Pergamon Press, Oxford UK, 480 p.

Pelto, M.S. 1996. Annual net balance of North Cascade glaciers, 1984–1994. *J. Glaciol.*, 42(140): 3–9.

Pelto, M.S., 1997: Reply to comments of Meier and others on "Annual net balance of North Cascade glaciers 1984–1994" by M. S. Pelto. *J of Glaciol*., 43(143): 193–196.

Post, A.S., and LaChapelle, E.R., 1962: Glacier Ice. The Mountaineers and University of Washington Presss, Seattle WA.

Walters, R.A., and Meier, M.F. 1989. Variability of glacier mass balances in Western North America. In Peterson, D.H., Aspects of climate variability in the Pacific and western Americas. *AGU, Geophysical Mono*. 55: 365–374.

Wold, B., and Haakensen, N. 1981. Glasiologiske Undersokelser 1 Norge 1979. *NVE, Rapport 3-81*.

Young, G.J., and Ommaney, C.S.L. 1984. Canadian hydrology and mass balance studies. *Geogr. Ann*., 66A: 169–182.