

tant to know just how his measurements fit into agreed standards for mass-balance measurement.

We hope that the author will respond to these questions and concerns. We would like to incorporate new data such as these into our broad analyses, but we and the community need to be sure that the methodology behind the numbers reported will stand up to scrutiny.

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SIR,

Reply to the comments of Meier and others on “Annual net balance of North Cascade glaciers, 1984–94” by Mauri S. Pelto

I welcome the opportunity to further explain the methods used by the North Cascade Glacier Climate Project (NCGCP) and to explore the shortcomings in standard mass-balance methodologies that have forced NCGCP to utilize a slightly different measurement system. I appreciate the concern of the authors (Meier and others, 1997) for the integrity of mass-balance records. Mark Meier in particular has long championed the importance of good mass-balance programs. I will address each of the five points raised in order.

The North American Committee on Climate and

Glaciers (1991), in examining glacier mass-balance standards, emphasized that, “Broad scope, regional glacier studies related to present benchmark sites are needed to determine the significance and representativeness of fluctuations in benchmark glaciers.” NCGCP was designed to carry out a regional mass-balance survey in the North Cascades. To complete this task required a few adjustments to the more time-consuming and costly standard methods without sacrificing accuracy.

(1) Measurement of accumulation in the accumulation area has been accomplished using probing and snow pits in almost all mass-balance studies. Probing has proved both successful and easy to use in almost all temperate and subpolar climate settings. In each case, the investigators rely on identification of a hardness discontinuity to distinguish the current year’s accumulation from older accumulation. LaChapelle (1954, 1965) noted that a maritime snow-cover surface develops, after its first year, a marked increase in ram resistance caused by refreezing, that can be easily detected by probing. This is the foundation of probing. Repeated use of this method by Norges Vassdrags- og Elektrisitetsvesen (NVE) (Østrem and Brugman, 1991) and others in their annual mass-balance surveys has demonstrated that this is the typical case, not the exception, throughout temperate regions. Ahlmann (1941), LaChapelle (1954), Schytt (1959) and Miller (1963) have also emphasized this point. Østrem and Brugman (1991) noted that, during a warm summer, a rigid summer crust develops that can be identified in the next year by probing. In the North Cascades, all summers are notably warm. Thus, the focus of Meier and others (1997) on the lack of a density discontinuity is misplaced, as it is rare and a problem suffered regardless of method. In some areas, such as southeast Alaska, additional ice lenses pose problems for probing. In the North Cascades, ice lenses are indeed rare in the late summer (Pelto, 1996).

All mass-balance investigators must ask if their soundings are accurate. Standard methods rely on a few snow pits to determine this. However, three or four snow pits scattered across a glacier serve as a poor check. NCGCP instead relies on extensive double-checking provided by observation of the annual layer in crevasses and, like NVE (Østrem and Brugman, 1991), begins each transect from a blue-ice area, so the initial depth is known. This provides extensive independent corroboration of accumulation depth that is not given by standard methods.

An incorrect statement by Meier and others (1997) is that measurement of snow depth using crevasse walls is known to be unreliable. I can find no such reference in the literature. I have found several statements in support of crevasse stratigraphy as a means to measure accumulation depth. A review of field glaciology is necessary to demonstrate why crevasse stratigraphy is, in most cases, at least as accurate as probing, coring and snow pits.

Probing, coring and snow pits are artificial incisions into the glacier to identify the annual layer. The annual layer is identified by the previous dirty summer surface which typically exists in most temperate and maritime glaciers (Ahlmann, 1941; Schytt, 1959; Østrem and Brugman, 1991). There is no reason why a natural incision provided by a vertically walled crevasse which intersects the same annual layer would be any less reliable. In fact, in extensive NCGCP tests (Pelto, 1996), crevasse measurements had a

lower standard measurement error in duplicate measurements. The annual layers in a crevasse on Rainbow Glacier are illustrated in Figure 1. Note the lack of ice lenses.

Crevasse stratigraphy was not initially used in mass-balance studies, because of the difficulty in mapping stratigraphy and retrieving density samples, as well as the lack of crevasses in some areas. NCGCP uses the crevasses only in place of probing to measure accumulation-layer thickness. The following examples emphasize the usefulness of crevasse stratigraphy.



Fig. 1. Annual accumulations in a vertically walled crevasse on Rainbow Glacier, Mount Baker, North Cascades. The several annual layers seen all show horizontal continuity and a lack of variation in layer thickness. There are no visible ice lenses.

Sharp (1951) examined in detail ice layers and lenses in the crevasse walls on Seward Glacier, Alaska. He noted that there was little difficulty in identifying layers of considerable lateral extent from crevasse to crevasse, and the tracing of annual layers in various crevasses is illustrated in Sharp (1951, fig. 7). In particular, the annual layers were distinguished by the extensive dirty layers. Miller and Field (1951) used crevasses to identify crevasse stratigraphy on Taku Glacier, Alaska, to a depth of 18 m in much greater detail than could have been done from a single core or snow pit. They found that the crevasse stratigraphy agreed well with snow pits and cores. Schytt (1959, fig. 3) gives a good example of “very distinct” annual stratification, and even the stratification of individual snowfalls. The crevasses were used to identify accumulation on the Rabots Glaciär, Sweden. Miller (1963) notes the success of crevasse stratigraphy in measuring snow depth on Taku Glacier by comparing snow-pit and coring studies to crevasses. Of course both snow pits and coring studies provide only a

point measure, crevasses a linear measure. Miller and others (1965) utilized crevasse stratigraphy to identify annual accumulation on the Khumbu glacier, Nepal. It was discovered by tracing the layers back to the 1954 layer, which had high tritium content due to atomic weapons tests, that two layers are deposited each year in the Mount Everest region. One layer is for the summer monsoon, and one for the winter monsoon.

The following are examples of illustrations that demonstrate my point. Post and LaChapelle (1971: 6–7) provide an excellent depiction of the annual layering in glaciers around the world. In two of the cases, the annual layers are distinct dirty layers that are of uniform thickness even in the blue-ice zone. This is the case on Columbia, Lower Curtis and Yawning Glaciers in the North Cascades. Post and LaChapelle (1971) explain the development of these layers: “The identification of each annual firn layer is based on the dust and dirt that accumulate on the glacier each year. Dust is thinly distributed throughout the winter and spring snow-pack and is not visible in the bright snow. As spring and summer melt progress, this dirt and dust accumulates on the ablation surface. Such an ablation-formed dirt horizon distinguishes one year’s accumulation from another”. Hambrey and Alean (1992) photographed annual layers from the Cordillera Blanca (p. 24) and from the Swiss Alps (p. 172), noting the appearance of Saharan dust on each summer surface. A final example of the visibility and horizontal continuity of the annual layers is a cover of the *Journal of Glaciology* (vol. 38, no. 130). In the North Cascades I have found that the annual dirt horizons are very distinct, generally horizontally continuous and ubiquitous.

It is sometimes possible that the annual layer is difficult to distinguish in a crevasse, because of a poorly developed summer icy-dirty layer. This difficulty is even more apparent in snow pits and cores, where the exposure is much more limited. The lack of dirt layers in crevasses is rare in the North Cascades and many other regions. In addition, since the dirt layer is used in snow pits and coring, it would be a problem suffered regardless of method. Only vertically walled crevasses, that yield readily identifiable annual layers where the annual layer is not distorted by a slump into the crevasse, can be utilized.

Through time, the glaciological community has forgotten the validity and usefulness of crevasse stratigraphy demonstrated in the above cited samples. Many of the initial developers of mass-balance field studies, including Field, LaChapelle, Miller, Schytt and Sharp, utilized crevasse stratigraphy. It is a time-efficient method for determining accumulation-layer thickness; however, it remains hazardous and is not practical for density measurements.

The remaining point regarding the accumulation zone is that figure 2 in Pelto (1996) is a rectangular grid. This is because Columbia Glacier is nearly crevasse-free. Each measurement transect begins and ends at fixed points on the bedrock edges of each glacier. Two probing teams are used and each can generally measure 200 points in a day, more than is necessary on these small glaciers. Coring and snow pits are not used any more by NCGCP, because they were found to be less accurate than crevasses, much too time-consuming, and the accumulation-layer density is constant late in the summer.

Standard methods reliant on the time-intensive methods of snow pits have in the U.S.A. often used very limited data

sets. On Gulkana Glacier in 1992 (March and Trabant, 1996), all accumulation measurements were made in three snow pits and using stakes within 60 m of these snow pits. This glacier has an area of 19.6 km². Is this sufficient? On South Cascade Glacier in 1993 and 1994 (Krimmel, 1994, 1995) four and five points, respectively, were used to determine annual balance on this glacier with an area of 2.0 km². Is this sufficient? Walters and Meier (1989) stated that "data from single observation points can be averaged over the glacier by weighting the data values and summing over the glacier. The weights must be determined from previous year's records." This simplification is being used by the U.S. Geological Survey on their benchmark glaciers for determining annual balance. Given the vast changes on South Cascade Glacier, it is likely that the weights of the past are not constant. When is this short-cut sufficient? The short-cut being used in many studies is reduced measurement density to control costs. The result is that, despite using standard methods, there is insufficient coverage. These glaciers can provide and have provided invaluable records, but is this still the case? We cannot, through more sophisticated analysis, continue to reduce the number of glaciers or measurements being completed and maintain or improve the quality and utility of glacier mass-balance records.

(2) Meier and others' second point refers to the statement that "ablation stakes are drilled or driven into the ice". I needed to add the words "and snow" at the end of the sentence, since during heavy-snow years new stakes are often driven through the snow and may or may not reach the ice, at which time drilling would be used. Multiple trips are made to each glacier. Each glacier has an observer whose sole task in early July is to make sure that ablation stakes will not melt out.

(3) Meier and others point out my lack of uniform use of the terms net annual balance and annual net balance. This is a good point, that has raised concern among mass-balance workers. The North American Committee on Climate and Glaciers (1991) noted "that the discussion about the definition of and difference between annual and net balance are of concern and that the terms were not being used uniformly". I represent the confused. Which definition do I use, since they are used differently, and often are too rigid to encompass many specific measurement methods? An example is provided by Gulkana Glacier (March and Trabant, 1996) where both annual and stratigraphic methods are used and where the net balance is determined between successive balance minima which occur at different times for different parts of the glacier, and are then combined for the entire glacier as if the minima occurred simultaneously. This combines the two methods where both annual and net balance are calculated; however, there is no single fixed date for stratigraphic methods or fixed minimum date for net balance. On South Cascade Glacier, Washington, the last measurement does not coincide with the balance minimum, and the net balance is estimated from air temperature; a fixed date is not used for measurements either (Krimmel, 1994). Thus, neither net nor annual balance is determined solely from measurements.

The aforementioned illustrate that many programs use a combination of stratigraphic and fixed-date systems. We should not confuse the two systems, but they can be combined. The examples also demonstrate that the definitions are often too strict to be practically applied and none of

these programs meet the definition of standard methods from Mayo and others (1972). Thus, the North American Committee on Climate and Glaciers (1991) recommended that more attention be given to explaining the timing and nature of the measurements since the standard is seldom exactly met. NCGCP measures, as do all programs, the stratigraphic thickness of the annual accumulation layer in the accumulation zone. This is done on fixed dates. Ablation is the observed ablation at the measurement sites for the entire year. These measurements are also carried out on a specific date. Net balance is defined as the change in mass balance between successive mass-balance minima (Mayo and others, 1972), whereas annual balance is defined as the change in snow, firn and ice storage between two fixed dates. NCGCP clearly uses the annual balance method. I appreciate this point being raised and will be more accurate in my declaration of which term I am using in the future.

(4) I have learned why no other glaciologists observe the annual balance on so many glaciers across a mountain range each year using intensive field methods. This is extremely arduous physical work. I train physically year around to be able to cover the necessary ground, and require exceptional conditioning from my assistants. The time required to measure all of the glaciers is exaggerated by Meier and others (1997) for two reasons: (i) Mass balance is measured at more than one glacier in two of the field areas (two at Mount Baker, four at Mount Daniels) (note Pelto, 1996, fig. 1), and thus there are only four field areas. (ii) In addition, these glaciers are small and require less time to measure, all being less than 1.5 km² in area, and only one greater than 1.0 km².

We arrive on the correct fixed date each year by being physically and logistically prepared to handle all weather conditions. In 13 years of fieldwork only 2 days have resulted in failure to complete measurements.

(5) I am bothered by the high annual balance cross-correlation coefficients too. I expected much more difference (Pelto, 1988) between glaciers and was wrong. The correlation with South Cascade Glacier is actually 0.67 vs the mean annual balance of North Cascade glaciers measured by NCGCP and ranges from 0.60 to 0.77 for individual glaciers. Figure 2 illustrates the variation of net balance on South Cascade Glacier (Krimmel, 1996) and annual balance on North Cascade glaciers measured by NCGCP. The similarity in annual trend is striking. Only 1990 shows a differential trend. If 1990 is removed from the correlation analysis, the correlation between NCGCP glaciers and South Cascade Glacier rises to 0.70. The lower mean net balance on South Cascade Glacier does reflect what A. Post (personal communication, 1996) has long maintained, that South Cascade Glacier is not representative of most North Cascades glaciers. Its rapid retreat throughout the 20th century indicates this point as well. Most North Cascades glaciers experienced a period of stability or growth between 1950 and 1975 (Tangborn, 1980; Pelto, 1993). A few have retreated continuously (Whitechuck, Honeycomb, Lyman and Hinman) as has South Cascade Glacier (Pelto, 1993). South Cascade Glacier is substantially different from most North Cascade glaciers but, as Figure 2 illustrates, not grossly different. I look forward to fully illustrating this point in a future paper. Jon Riedel has measured in a preliminary fashion annual balance on several North Cascades glaciers for the last 3 years. The methods are unpublished as

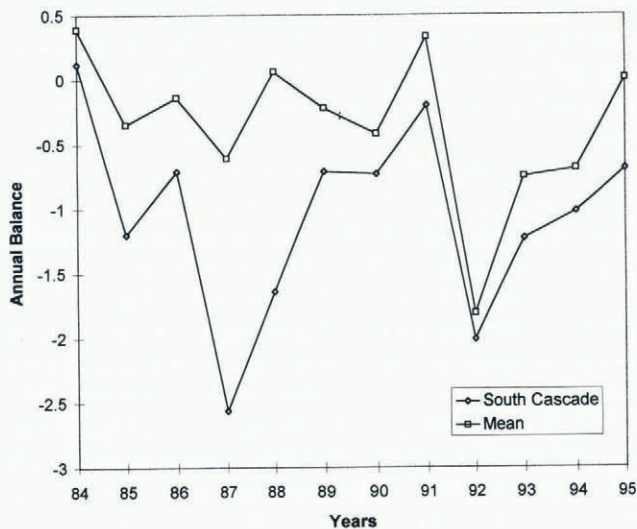


Fig. 2. Mean annual balance of the eight North Cascade glaciers observed by NCGCP, and net balance of South Cascade Glacier, from Krimmel (1996).

are the incomplete results; however, in several meetings with Riedel I have found that the results for 1994 and 1995 that have been shared with me fit closely indeed to my observations.

CONCLUSION

It must be emphasized that we have been too complacent in relying on very narrowly defined standard mass-balance measurement methods which, in cases such as Sentinel Glacier, Canada, proved unreliable, and on Blue Glacier, Washington, and Maclure Glacier, California, too expensive to maintain. The result is an inadequate network in North America. We cannot, in North America, expect an increase in funds to expand the network, or to effectively utilize satellite imagery for small alpine glaciers. Satellite imagery is not accurate enough, nor affordable; thus we must look to be more cost-efficient. Although physically dangerous, the use of crevasse stratigraphy, where appropriate, is accurate and efficient. Only an experienced, cautious and knowledgeable glacier traveller can rely on this method. I had travelled more than 1500 km on ski or foot across more than 40 different glaciers conducting glacier studies before I felt comfortable utilizing this technique.

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