Correspondence

The Editor,
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SIR,

Comments on "Annual net balance of North Cascade glaciers, 1984–94" by Mauri S. Pelto

The mass balance is the critical link in understanding between climatic change and fluctuations of glaciers, and this understanding is assuming greater importance as society worries about sea-level rise, water-supply reductions and other possible consequences of our changing climate. Unfortunately, too few data exist on the mass balances of the Earth's glaciers, making it difficult to establish this link with confidence. We therefore welcome the release of new data, especially data which represent eight to ten glaciers and a 10 year time series.

Pelto's most recent paper (Pelto, 1996) adds several years of new data and some additional analyses to his previous papers on this subject (e.g. Pelto, 1987, 1988, 1993). These data might be a useful addition to the global data set on glacier mass balances, which is under active study by many of us. In order to include new information in such analyses, one has to scrutinize the data very carefully, as the results of any broad compilation can be no better than the quality of the input data. In order to have confidence in these North Cascades data, we believe that additional explanation of his field data-collection methods is needed. We note the following points which engender questions:

(1) *The balance in the accumulation area.* The author states that he includes more measurement points or larger point densities than do other workers in the U.S.A., Canada, Norway or Switzerland. We would like to know more about how he obtains these data points: probing with a copper tube and a 1 kg weight is, in our experience, inadequate for sounding summer snowpacks in the North Cascades which are thick, dense and contain icy horizons, and which sometimes do not show a major hardness discontinuity across the summer surface. He also measures the depth to summer surface on crevasse walls, a method that is known to be unreliable and which is therefore not used by many investigators, in spite of its convenience. Experience at South Cascade and Blue Glaciers and similar glaciers has shown that summer surfaces are not always marked by dust layers, and such layers may be created by dust-raising storms at other times of year. His figure 2, showing a measurement network, looks like a rectangular grid, which would suggest a major probing project but which would not be expected if many of the measurements were made on crevasse walls. Were surveys conducted to locate these measurement points? In our experience, it would take an experienced team with an efficient probe several days to measure 200 points reliably on one of these glaciers; one would also expect to allow time for coring or pit digging to be sure of identifying the true summer surface.

(2) *The balance in the ablation area.* We are sure that the author has made a mistake in implying that long wooden stakes could be driven into the ice of the ablation area. It is hard to imagine how the net balance of up to −7 m w.e., as has been seen commonly near the terminus on nearby South Cascade Glacier, could be measured with stakes 3.3 m long, visited only once or perhaps twice per year. Only with the most fortuitous timing on multiple trips could one expect to revisit stakes before they loosened and degraded the record. Deep drilling (more than 7 m) could be employed, but the drilling would take time and one would need to ensure that the wooden stakes did not float up. In our experience, setting deep stakes to measure the ice melt over the ablation area just once on one glacier would take an experienced party at least a full day even on one of the small ice masses studied here.

(3) *The mass-balance computation system.* Pelto confuses systems: he refers to Mayo and others (1972), but the thrust of that reference, as well as the International Hydrological Decade standards and published guides that are adhered to internationally, is that the *fixed-date* and *stratigraphic* systems should not be confused. He states that, "[a]nnual balance is the difference between annual snow accumulation and (ablation)" (p. 3), which is imprecise, and he measures neither. Pelto seems to measure to the summer surface in the accumulation zone (stratigraphic system) in late July/early August, perhaps with a check in late September, and records the balance in the ablation zone on a fixed date. He confuses the issue by using the title, "Annual net balance ...", and referring elsewhere to "net annual balances"; are these net balances or annual balances? What are they?

(4) *Field schedule.* Pelto states, "Because all of the sites are accessed by backpacking, it has not been a problem to reach each glacier at the right date" (p. 5). We would expect to spend a minimum of 1 d packing in, 1 or 2 d in the accumulation basin, 1 d in the ablation area, 1 d packing out, per single glacier visit, which comes to something like a 40 d field season to measure eight glaciers just once, and with no allowance for bad weather, tool or instrument failure, recuperation or other contingencies. End-of-summer (late September) observations would add another like period. We would be curious to know how all of these measurements were made in the short times and on the "right dates" as reported.

(5) *"Cross-correlation" analysis.* The correlation coefficients reported (0.83–0.97; average 0.93) are extraordinarily high. We have seen such high correlations only between adjacent stakes on one glacier, or between glaciers in a single small mountain basin (e.g. Limmern-Plattalva basin; Tuyuksu basin). Typical correlation coefficients between glaciers in mountain areas similar to the North Cascades are, in our experience and in the literature, rarely higher than 0.8, for obvious reasons. Note that the correlation coefficient of the carefully measured South Cascade Glacier (in the same range) with the glaciers measured by Pelto is only 0.64. Is South Cascade Glacier grossly different from its neighbors? We see no evidence that it is. J. Riedel (personal communication, 1996) also reports that Pelto's results do not correlate well with the four glaciers he measures for net mass balance in the North Cascades. Because of this, and the uncertainty about what is actually being measured by Pelto, it is impor-

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

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