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Mass balance of Siachen Glacier, Nubra valley, Karakoram Himalaya: facts or flaws?

Bhutiyani (1999) reported estimates for 1986–91 of the annual mass balance of Siachen Glacier, Karakoram. He solved the water balance of the catchment tributary to the source of the Nubra River, and reported a 5 year average balance for Siachen Glacier of –0.5 m w.e. a^{-1}. Our analysis reveals a discrepancy in this estimate, due to neglect of a considerable extent of glacier ice (~249 km^2) that is actually within the Nubra catchment. Correction of the error reduces the mass-balance estimate to –0.23 m w.e. a^{-1} even though other possible errors (e.g. overestimation of evaporation) are not corrected. This revised estimate is a lower bound. An upper-bound estimate suggests that in fact the mass balance may have been near zero, which would be consistent with recent studies and would extend the duration of the Karakoram anomaly.

Bhutiyani (1999) is still the only study reporting in situ, whole-glacier measurements of mass balance, and the only study of any kind indicating substantial mass loss, in the Karakoram. This may explain why it has been cited in at least 14 publications (e.g. Cogley, 2011). However, a recent remote-sensing study shows no substantial change in glacierized area in the Karakoram during an overlapping study period (Bhambri and others, 2013), and the Bhutiyani measurement may conflict with evidence for the Karakoram anomaly identified by Hewitt (2005).

Bhutiyani (1999) used measurements of precipitation and discharge over the period 1986–91. Precipitation was measured over the glacier area using gauges and stakes. In addition, gains by avalanching from valley sides were calculated explicitly. The discharge was measured ~200 m downstream of the terminus of Siachen Glacier, and was assumed specific to the glacier area, not to the entire catchment. Evaporation was calculated as a function of annual mean temperature at a single point at 4800 m a.s.l. and was extrapolated over the whole catchment, neglecting the area–altitude distribution of the glacier and the vertical temperature gradient. The annual losses by evaporation, which range from 14% to 23% of ablation, are probably overestimated by Bhutiyani (1999) since the temperature measurement station is lower, and therefore warmer, than ~82% of the area of Siachen Glacier (Bhutiyani, 1999, table 1). Moreover, it is plausible that evaporation may be roughly balanced by condensation in a glacial environment (Aizen and others, 1997). However, the main issue raised in the present study is catchment area. Although Bhutiyani (1999) discussed possible errors in estimates of precipitation and discharge, he did not explain his delineation of the glacier catchment.

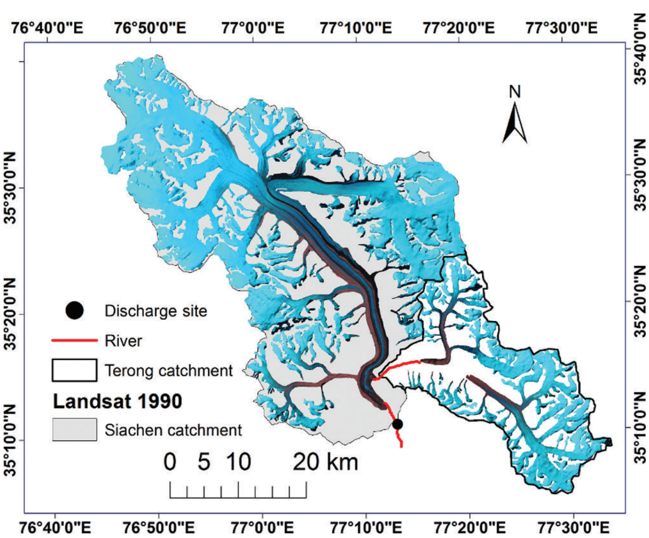

Fig. 1. The catchment tributary to the source of the Nubra River, with the extent of ice cover inside the catchment in 1990.

Runoff in specific units (m w.e. a^{-1}) will be incorrectly calculated if discharge measured at a point ($m^3 a^{-1}$) is divided by the wrong catchment area (m^2). In measurements of glacier mass balance by the hydrological method, the catchment is defined by glacier boundaries, but the water balance of the ice-free areas above the point of discharge must be accounted for (Cogley and others, 2011).

We have used the Shuttle Radar Topography Mission (SRTM) (90 m) digital elevation model (DEM) to delineate the catchment of the Nubra River at the terminus of Siachen Glacier and have found an area of 2056 km^2 (Fig. 1). The catchment includes North and South Terong Glaciers, hereafter referred to as 'the Terong Glaciers'. The river originating from the Terong Glaciers meets Siachen Glacier ~5.3 km above its terminus. Its flow must be presumed to mix with the flow of meltwater from Siachen Glacier, and the combined flow must emerge from the terminus of Siachen. Comparison of Figure 2 with Figure 1 shows that Bhutiyani (1999) omitted the Terong Glaciers from his calculations.

Landsat imagery of 29 June 1990 (available at ftp.glcf.umd.edu) gives the position of the terminus of Siachen Glacier at the time of the Bhutiyani study (Fig. 1). Siachen Glacier, which is 74 km in length, did not change its terminus position significantly during 1995–2008 (Ganjoo and Koul, 2009). Moreover, Bhutiyani (1999) mentions no change and shows a very similar glacier outline (Fig. 2). Therefore, the terminus position and total area of Siachen Glacier are assumed here to be stable.

We have measured glacier areas from outlines in the glacier inventory of the International Centre for Integrated Mountain Development (ICIMOD) (Bajracharya and Shrestha, 2011). The glacierized area inside the Siachen catchment outlined by ICIMOD is 971 km^2. The value is not very different from Bhutiyani's 987 km^2. In the ICIMOD inventory, the glacierized area inside the Terong catchment is 248 km^2. Superimposing the ICIMOD glacier outlines on the Landsat imagery of 1990, we found a small change at the terminus of South Terong Glacier. After incorporating this change, the total Terong Glaciers area (including small glaciers) was found to be 249 km^2 in 1990. Thus our estimate of the total glacierized area tributary to the terminus of Siachen Glacier in 1990 is 1220 km^2.

The flow of the Nubra River measured at the discharge station and used by Bhutiyani (1999, table 3) must come not only from Siachen Glacier and the Terong Glaciers but also from a few dozen smaller glaciers and a considerable expanse of ice-free terrain. It would be impractical to re-do Bhutiyani's entire calculation with allowance for the omitted glacierized area, but by assuming that runoff (discharge divided by contributing area) is the same from each of these three parts of the catchment it is possible to estimate an upper bound for the mass balance of Siachen Glacier. It is an upper bound because runoff from the ice-free terrain is likely to be small once all the snow has melted. In Table 1 this re-scaling of runoff and re-estimation of mass balance (which is a rough estimation given the sparse data) is done for each of Bhutiyani's five mass-balance years and for the whole 5 year period. The upper bounds for mass balance in row 13 of the table, with positive mass balance in four of the five years, can be compared with the lower bounds in row 20, which were obtained, after re-scaling of runoff, by assuming (as did Bhutiyani in effect) that runoff from the ice-free terrain is zero. Thus only the Terong and other small glaciers contribute runoff in addition to that from Siachen Glacier. The lower-bound calculations give a 5 year average mass balance of –232 mm w.e. a^{-1}, almost 55% smaller than the –515 mm w.e. a^{-1} of Bhutiyani (1999). It should be noted that a plausible overestimation of evaporation is not considered in these calculations.

Catchment area plays a vital role in hydrological mass-balance measurement. Bhutiyani (1999) did not give due attention to this fact. Our recalculation of the mass balance of Siachen Glacier, using total catchment area to obtain an upper bound and total glacierized area to obtain a lower bound, suggests that the balance for 1986–91 was actually between +0.22 and –0.23 m w.e. a^{-1}. Hence, coupled with a probable overestimate of mass loss by evaporation, the correction of the Bhutiyani calculations for inaccurate meltwater losses appears to be consistent with a mass balance near zero for Siachen Glacier during 1986–91. In turn this would be consistent with recent geodetic measurements (Gardelle and others, 2012) and would increase the known duration of the Karakoram anomaly first proposed by Hewitt (2005).

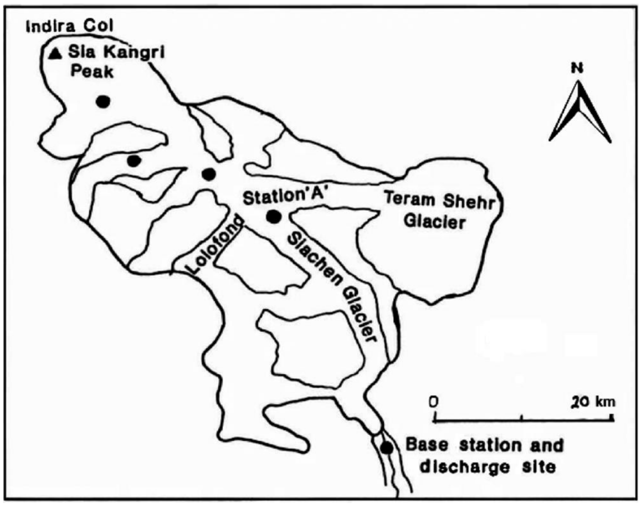

Fig. 2. The outline of Siachen Glacier given by Bhutiyani (1999), showing the discharge station but no Terong Glaciers. Dots mark precipitation measurement sites. At Station 'A', temperature was also measured.

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Table 1. Recalculation of runoff, and upper and lower bounds (based on total catchment area and total glacierized area, respectively) of the mass balance of Siachen Glacier for the period 1986–91

Row	Quantity	1986/87	1987/88	1988/89	1989/90	1990/91	Mean
1	*Areas*						
2	*S* Glacierized in Siachen	971	971	971	971	971	971
3	*S* Glacierized in Terong	249	249	249	249	249	249
4	*S* Glacierized (total)	1220	1220	1220	1220	1220	1220
5	*S* Ice-free	836	836	836	836	836	836
6	*S* Catchment	2056	2056	2056	2056	2056	2056
7	*Upper bounds*						
8	*R* Bhutiyani	1255	1488	814	1598	1778	1387
9	$\alpha 1 = S$ Siachen/S Catchment	0.47	0.47	0.47	0.47	0.47	0.47
10	$R1 = \alpha 1 \times R$ Bhutiyani	593	703	384	755	840	655
11	$\Delta R_U = R$ Bhutiyani $- R1$	662	785	430	843	938	732
12	*B* Bhutiyani	–488	–565	358	–794	–1084	–515
13	$B_U = B$ Bhutiyani $+ \Delta R_U$	174	220	788	49	–146	217
14	*Lower bounds*						
15	*R* Bhutiyani	1255	1488	814	1598	1778	1387
16	$\alpha 2 = S$ Siachen/S Glacierized	0.80	0.80	0.80	0.80	0.80	0.80
17	$R2 = \alpha 2 \times R$ Bhutiyani	999	1184	648	1272	1415	1104
18	$\Delta R_L = R$ Bhutiyani $- R2$	256	304	166	326	363	283
19	*B* Bhutiyani	–488	–565	358	–794	–1084	–515
20	$B_L = B$ Bhutiyani $+ \Delta R_L$	–232	–261	524	–468	–721	–232

Notes: *S*: area (km^2); *B*: mass balance (mm w.e. a^{-1}), from table 3 of Bhutiyani (1999); *R*: runoff (mm w.e. a^{-1}), from table 3 of Bhutiyani (1999); $\alpha 1$: ratio of Siachen area to total catchment area; $\alpha 2$: ratio of Siachen area to total glacier area; *R*1: estimated runoff for upper bound; *R*2: estimated runoff for lower bound; ΔR_U (U: upper), Δ_L (L: lower): difference of given and estimated runoffs (mm w.e. a^{-1}); *B*: mass balance of Siachen (mm w.e. a^{-1}), from table 3 of Bhutiyani (1999); B_U: upper bound of mass balance (mm w.e. a^{-1}) based on total catchment area; B_L: lower bound of mass balance (mm w.e. a^{-1}) based on total glacierized area.

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REFERENCES

Aizen VB, Aizen EM, Dozier J, Melack JM, Sexton DD and Nesterov VN (1997) Glacial regime of the highest Tien Shan mountain, Pobeda–Khan Tengry massif. *J. Glaciol.*, **43**(145), 503–512

Bajracharya SR and Shrestha B (2011). *The status of glaciers in the Hindu Kush–Himalayan region*. International Centre for Integrated Mountain Development, Kathmandu

Bhambri R, Bolch T, Kawishwar P, Dobhal DP, Srivastava D and Pratap B (2013) Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. *Cryosphere*, **7**, 1385–1398 (doi: 10.5194/tc-7-1385-2013)

Bhutiyani MR (1999) Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram Himalaya, India. *J. Glaciol.*, **45**(149), 112–118

Cogley JG (2011) Present and future states of Himalaya and Karakoram glaciers. *Ann. Glaciol.*, **52**, 69–73 (doi: 10.3189/172756411799096277)

Cogley JG and 10 others (2011) *Glossary of glacier mass balance and related terms*. (IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2) UNESCO–International Hydrological Programme, Paris

Gardelle J, Berthier E and Arnaud Y (2012) Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geosci.*, **5**, 322–325 (doi: 10.1038/NGEO1450)

Ganjoo RK and Koul MN (2009) Is the Siachen glacier melting? *Current Sci.*, **97**(3), 309–310

Hewitt K (2005) The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. *Mt. Res. Dev.*, **25**(4), 332–340