

# Spatially variable shrinkage of glaciers in the Annapurna Conservation Area, Nepal, 2000 to 2016

Arminel M. Lovell, J. Rachel Carr and Chris R. Stokes

## Supplementary information

**Table S1:** DEM correction and uncertainties. The shifts in the x,y and z directions to co-register each DEM to the SRTM with the exception of the ASTER14DEM which was co-registered to the SPOT7 Lower DEM, the mean, standard deviation and NMAD of the off-glacier stable terrain before and after DEM correction and the uncertainty calculated for each DEM of difference.

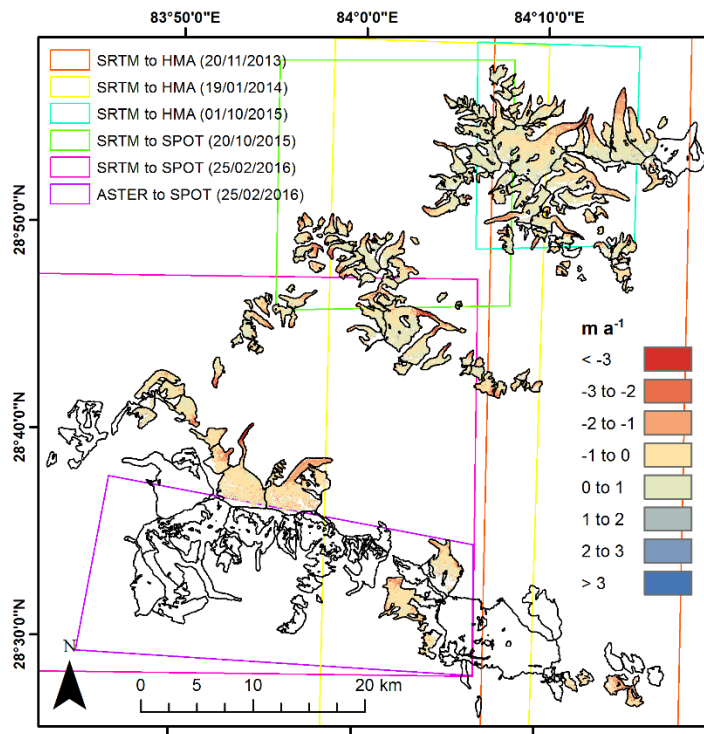
Imagery name	Co-registration shifts			Pixel sum	Before correction			After correction			dh/dt uncertainty ( $\pm m a^{-1}$ )
	x	y	z		Mean (m)	SD (m)	NMA D (m)	Mean (m)	SD (m)	NMA D (m)	
AST14DEM_0031215 2000052420	-27.69	5.44	37.82	180717	-42.00	28.55	21.41	0.00	23.46	16.66	0.97
HMA_DEM8m_AT_20131120_0508	1.79	-3.34	34.12	682731	-34.48	9.75	6.95	0.00	9.50	6.20	0.23
HMA_DEM8m_AT_20140119_0459	4.22	-4.44	34.69	756258	-35.33	13.76	7.38	0.09	13.61	7.17	0.23
HMA_DEM8m_AT_20151001_0511	4.67	-2.62	29.65	141775	-30.16	7.55	5.32	-0.51	7.55	5.32	0.33
SPOT7_UPPER_DEM	2	-7.02	32.55	391993	-32.26	10.25	6.95	0.29	10.25	6.95	0.34
SPOT7_LOWER_DEM	4.88	-1.8	18.82	617871	-18.43	11.01	8.75	0.00	10.86	8.73	0.77

**Table S2:** The variation (standard deviation) of repeat digitised outlines for 10 debris-free and 10 debris-covered glaciers, selected at random.

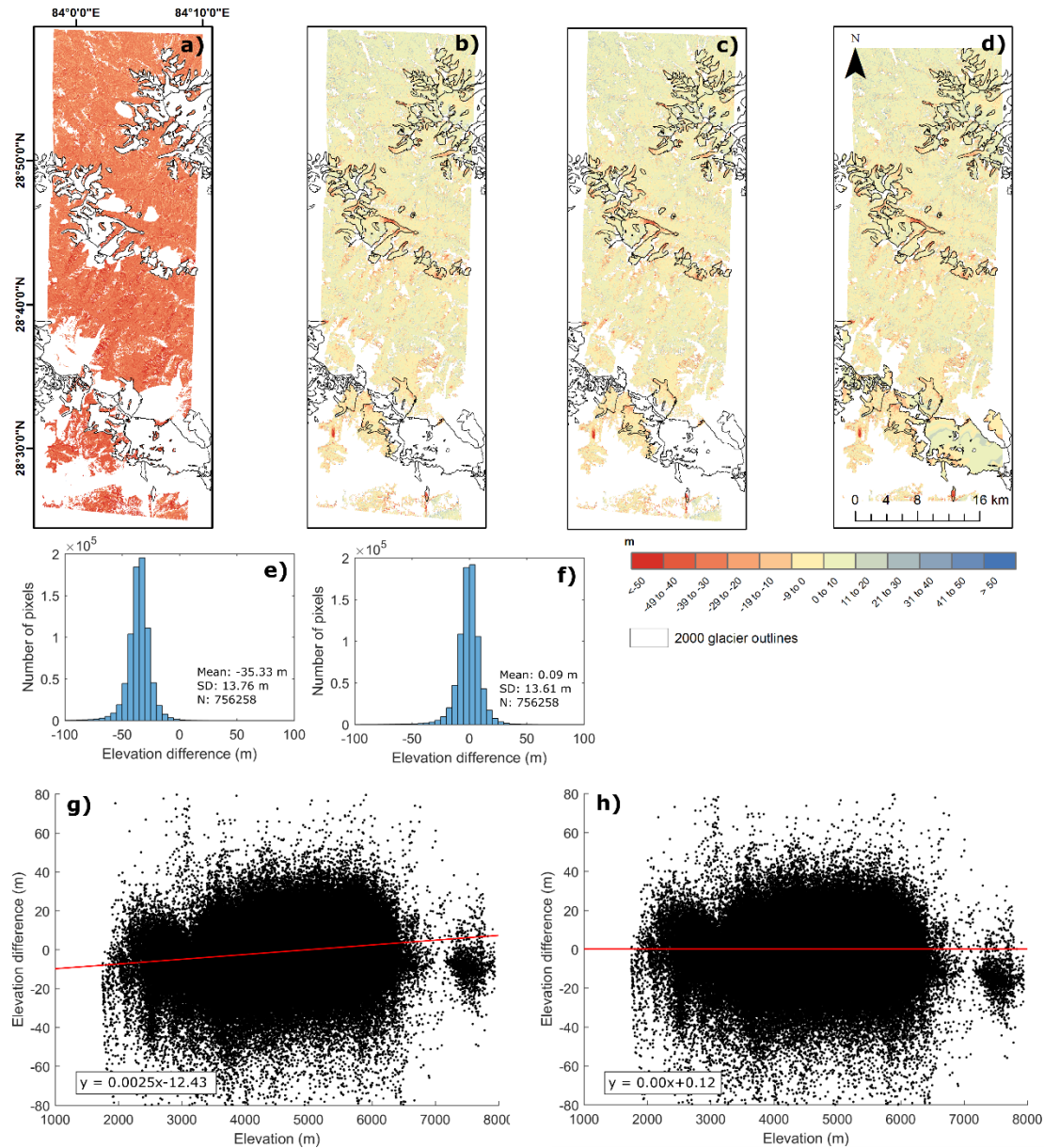
Glacier	Debris covered	Area (km <sup>2</sup> )	Std (%)
Kawache	Y	0.40	1.75
KG003	N	1.81	4.25
KG005	Y	7.68	2.51
KG016	Y	7.22	0.56
KG033_1	N	0.16	1.43
KG040	N	0.45	5.13
M002	Y	4.31	0.85
M003	Y	17.35	0.43
M005_2	N	0.30	0.66
M008	Y	6.59	1.80
M011	N	1.29	2.50
M017	Y	2.26	1.56
M024	N	1.78	0.54
M025	N	0.30	1.60
M042_1	N	0.93	1.26
M045	N	2.85	0.53
M063	Y	2.35	4.00
M100	N	0.25	2.37
MSM002	Y	0.83	2.64
MSM023	Y	1.75	0.93
Mean			<b>1.87</b>

**Table S3:** The mean and standard deviation of point-sampled velocities on stable terrain (vegetated and with shallow slopes) in the ACA for the 2002 and 2016 velocity maps and the number of points sampled in each map. The disparity in the number of sampled points between the maps is due to the pre-determined points coinciding with data voids in one or other of the maps.

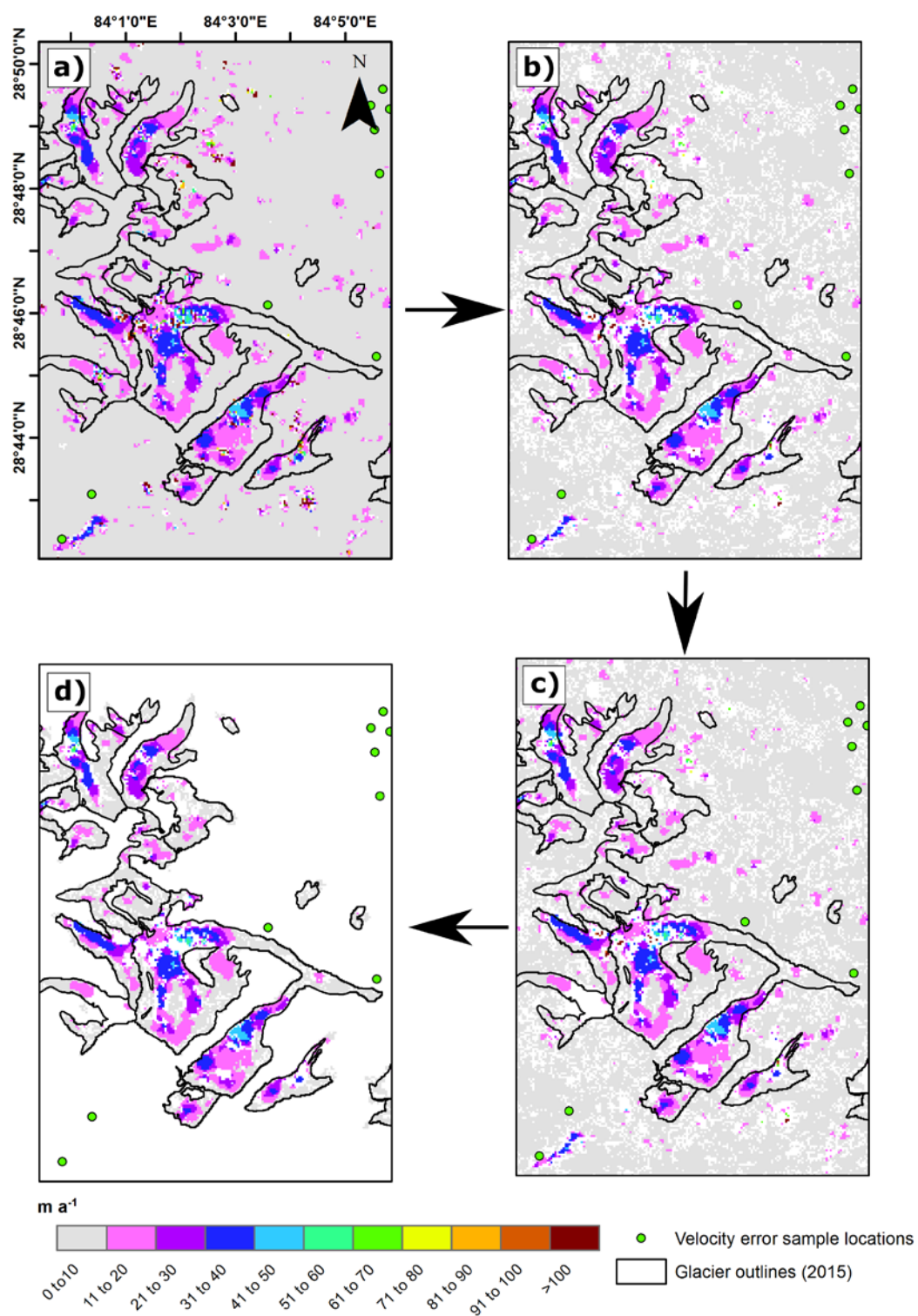
Interval	Mean velocity error (m a <sup>-1</sup> )	St dev (m a <sup>-1</sup> )	Number of sampling points
03/01/2002 to 05/12/2002	4.32	4.08	177
02/01/2016 to 10/12/2016	2.07	2.49	251



**Figure S1:** Surface elevation changes (2000 to 2013/16) showing the footprints of the different DEM difference maps.

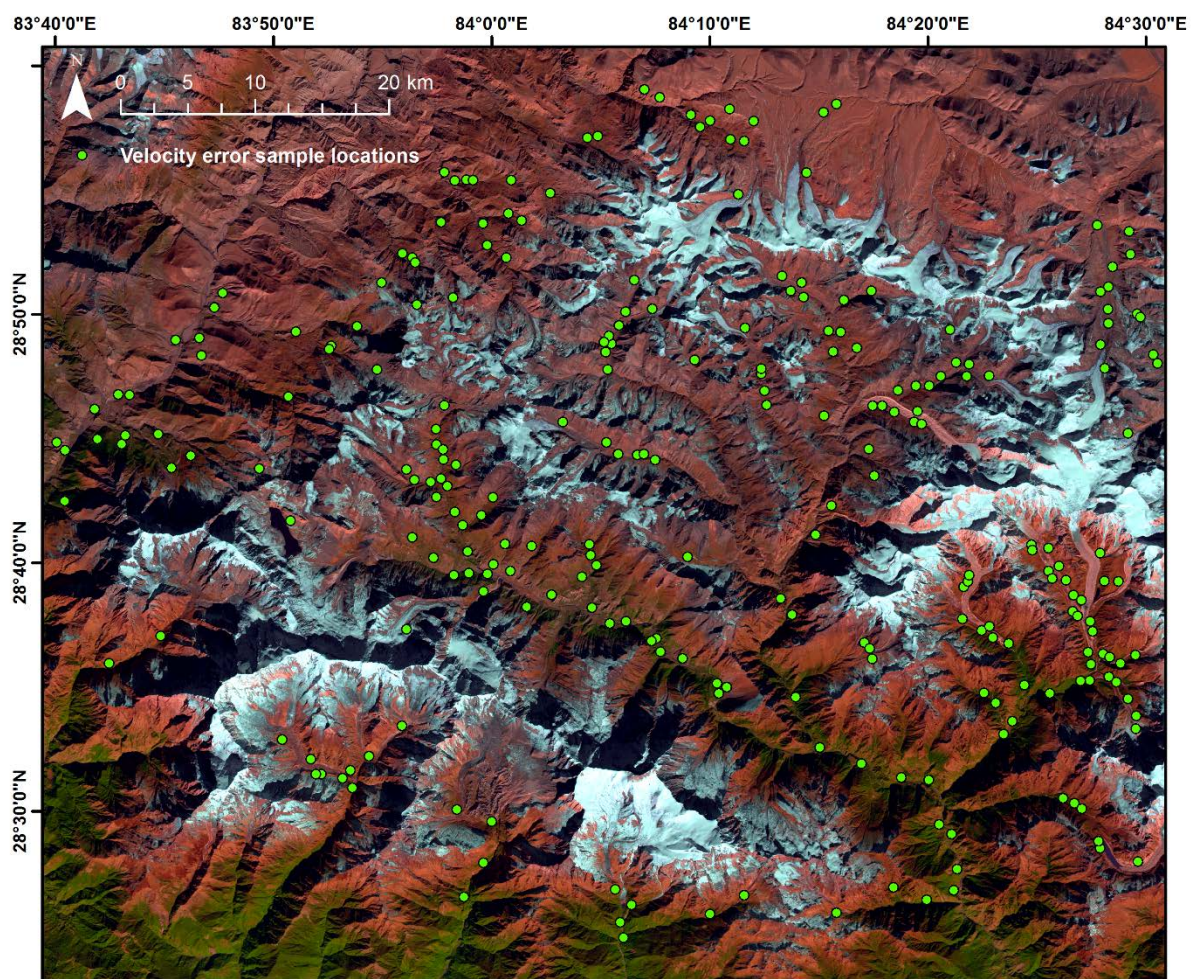


**Figure S2:** Example workflow to correct, filter and fill the surface elevation difference maps using the surface elevation difference map derived from the SRTM GDEM and the HMA\_DEM8m\_AT\_20140119\_0459 DEM. a) Elevation differences on stable terrain prior to co-registration and correction, b) after co-registration and correction, c) after filtering, d) after filling, e) off-glacier statistics of surface elevation difference on stable terrain before correction and f) after correction, g) elevation difference plotted against elevation on stable terrain where the trend-line shows an elevation-dependent bias and h) elevation difference plotted against elevation on stable terrain after the elevation-dependent bias has been corrected.

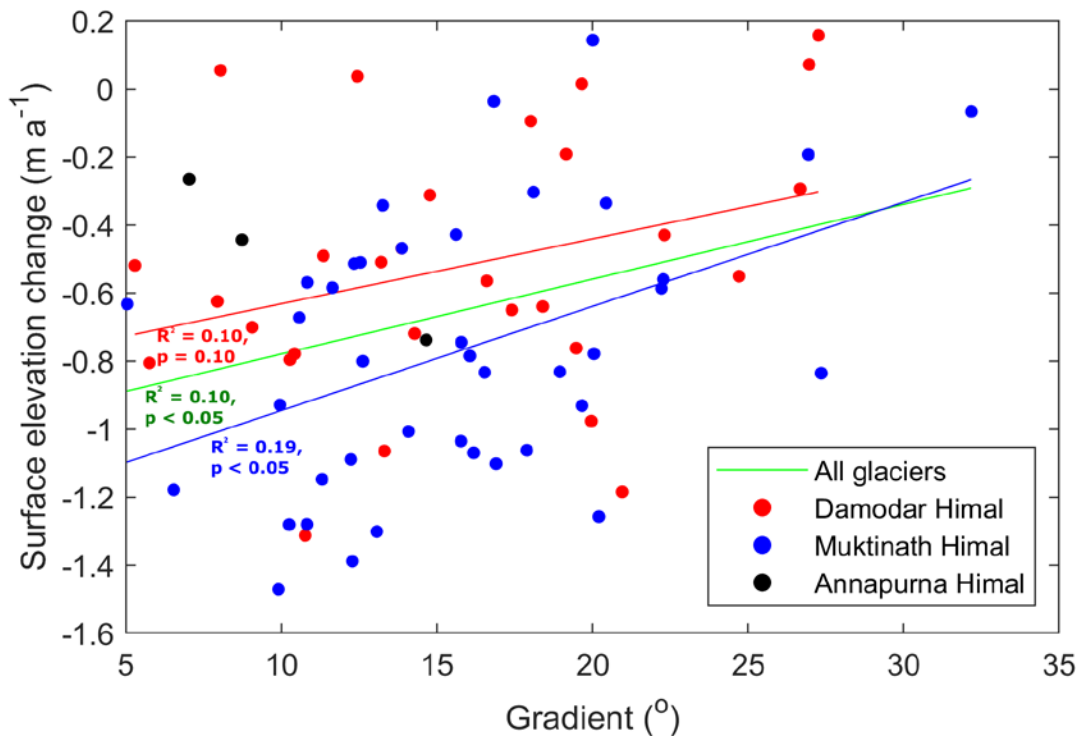


**Figure S3:** The surface velocity processing workflow, a) shows the velocities before post-processing, b) velocities after the magnitude and direction filter was applied, c) velocities after additional manual editing was applied and d) final velocity map. Glacier outlines from 2000.

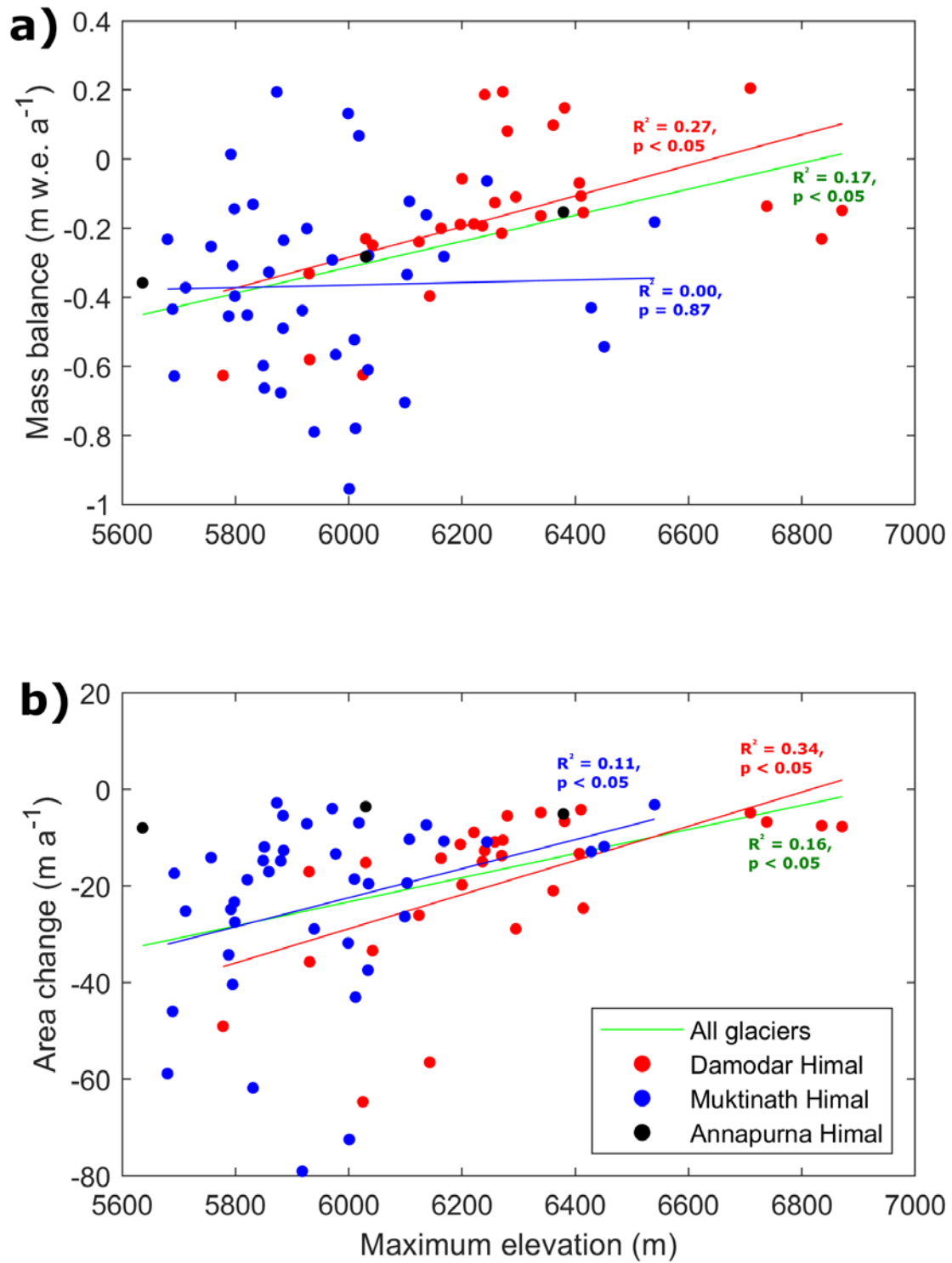




**Figure S4:** Velocity error sampling point locations.

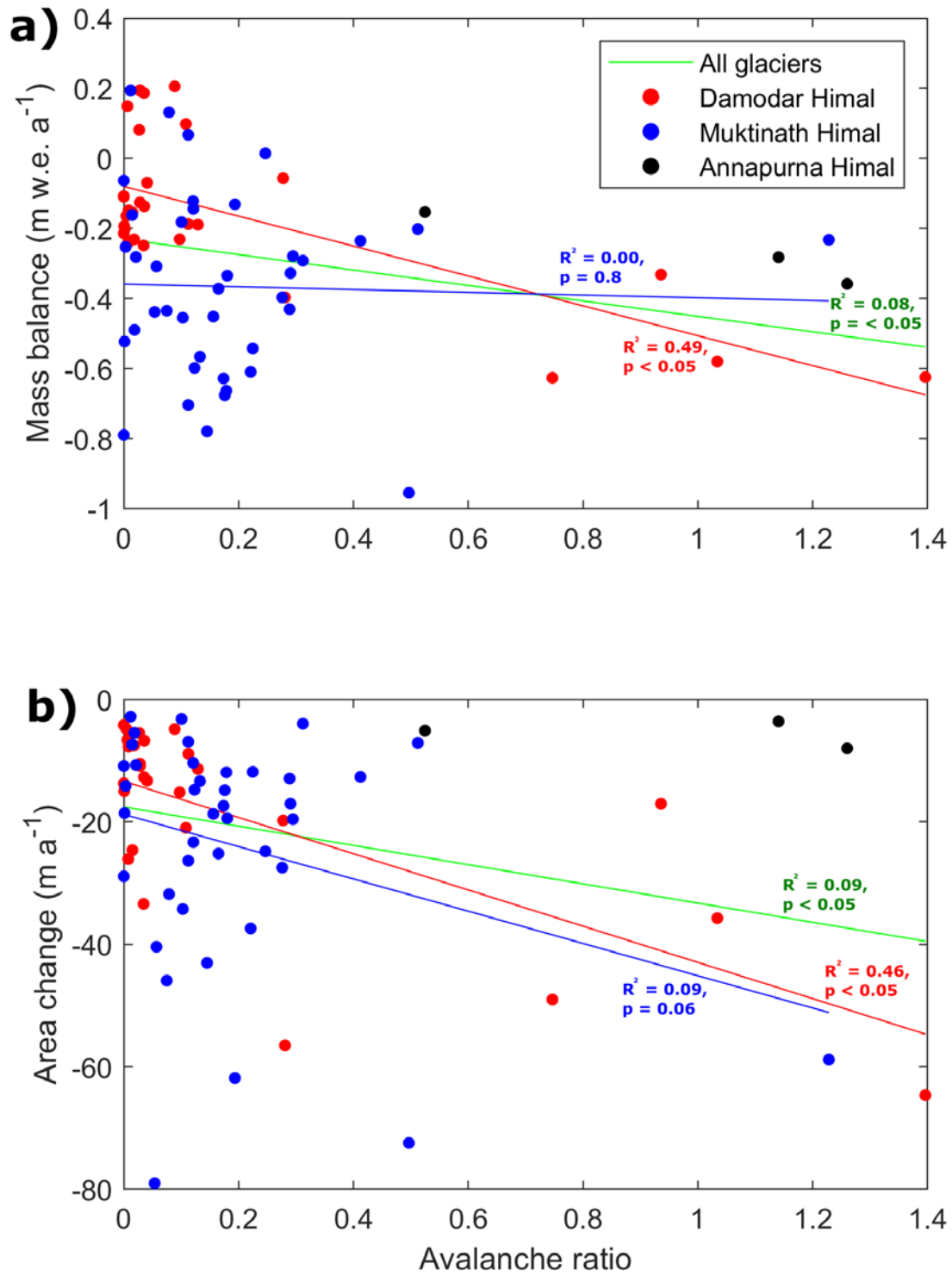


**Figure S5:** Scatterplot of mean gradient of the ablation zone and mean surface elevation change of the ablation zone (n=72). The green line is the line of best fit for all glaciers and the red and blue lines are the lines of best fit for the Damodar Himal and Muktinath Himal, respectively. The Annapurna Himal did not have enough data points for a line of best fit. Each line is labelled with its  $R^2$  and p-values, in corresponding colours.



**Figure S6:** Scatterplots of a) mass balance against maximum elevation ( $n=72$ ) and b) area change against maximum elevation ( $n=72$ ). The green line is the line of best fit for all glaciers and the red and blue lines are the lines of best fit for the Damodar Himal and Muktinath Himal, respectively. The Annapurna Himal did not have enough data points for a line of best fit. Each line is labelled with its  $R^2$  and  $p$ -values, in corresponding colours.





**Figure S7:** Scatterplots of a) mass balance against avalanche ratio ( $n=72$ ) and b) area change against avalanche ratio ( $n=72$ ). The green line is the line of best fit for all glaciers and the red and blue lines are the lines of best fit for the Damodar Himal and Muktinath Himal, respectively. The Annapurna Himal did not have enough data points for a line of best fit. Each line is labelled with its  $R^2$  and p-values, in corresponding colours.