



Supplement of

Cast shadows reveal changes in glacier surface elevation

Monika Pfau et al.

Correspondence to: Monika Pfau (monika.pfau@arcor.de)

The copyright of individual parts of the supplement might differ from the article licence.

Supplement S: Additional tables

Table S1: Landsat bands used to map shadows on glaciers, including image metadata, the threshold to manually classify shadows on glaciers, and the number of bearing lines that cross shadows on glaciers. TM: Thematic Mapper, ETM+: Enhanced Thematic Mapper, OLI: Operational Land Imager, SRTM-1: DEM of the Shuttle Radar Topography Mission (30m resolution), swissALTI3D: DEM of Switzerland (5 m resolution), GLO-90: Copernicus DEM (90m resolution)

Glacier	Acquisition Date	Landsat Mission	Band	Azimuth	Elevation	File Name in GeoTIFF format	Threshold between shadow and no-shadow	Number of bearing lines drawn
Great Aletsch	06.02.1987	TM	2	146.96	21.95	LT05_L1TP_195028_19870206_20170213_01_T1_sr_band2	5,500	106 (SRTM-1, swissALTI3D), 107 (GLO-90)
Great Aletsch	18.02.1988	TM	2	147.49	26.38	LT05_L1TP_194028_19880218_20180215_01_T1_sr_band2	5,500	106 (SRTM-1), 105 (GLO-90, swissALTI3D)
Great Aletsch	11.02.1989	TM	2	148.32	25.39	LT05_L1TP_195028_19890211_20180215_01_T1_sr_band2	5,500	105 (SRTM-1), 106 (GLO-90)
Great Aletsch	07.02.1990	TM	2	146.88	22.34	LT05_L1TP_194028_19900207_20180219_01_T1_sr_band2	5,500	105 (SRTM-1, swissALTI3D), 106 (GLO-90)
Great Aletsch	01.02.1991	TM	2	147.64	20.64	LT05_L1TP_195028_19910201_20180215_01_T2_sr_band2	5,500	106 (SRTM-1, swissALTI3D), 105 (GLO-90)
Great Aletsch	06.02.1993	TM	2	147.11	22.21	LT05_L1TP_195028_19930206_20180215_01_T1_sr_band2	5,500	106 (SRTM-1), 105 (GLO-90, swissALTI3D)
Great Aletsch	25.02.1994	TM	2	144.21	28.10	LT05_L1TP_195028_19940225_20180215_01_T1_sr_band2	5,500	100 (SRTM-1), 101 (GLO-90, swissALTI3D)
Great Aletsch	21.02.1995	TM	2	142.356	25.60	LT05_L1TP_194028_19950221_20180215_01_T1_sr_band2	5,500	102 (SRTM-1, swissALTI3D), 101 (GLO-90, swissALTI3D)
Great Aletsch	21.02.1996	TM	2	142.07	23.06	LT05_L1TP_195028_19960215_20180215_01_T1_sr_band2	5,500	102 (SRTM-1, GLO-90, swissALTI3D)
Great Aletsch	01.02.1997	TM	2	148.58	21.19	LT05_L1TP_195028_19970201_20180215_01_T1_sr_band2	5,500	108 (SRTM-1), 107 (GLO-90, swissALTI3D)
Great Aletsch	20.02.1998	TM	2	148.90	27.88	LT05_L1TP_195028_19980220_20180215_01_T1_sr_band2	5,500	105 (SRTM-1, swissALTI3D), 106 (GLO-90)
Great Aletsch	10.02.2000	TM	2	149.53	24.20	LT05_L1TP_195028_20000210_20171211_01_T1_sr_band2	5,500	106 (SRTM-1, GLO-90, swissALTI3D)
Great Aletsch	14.02.2004	TM	2	150.35	25.93	LT05_L1TP_194028_20040214_20180311_01_T1_sr_band2	5,500	107 (SRTM-1), 106 (GLO-90), 108 (swissALTI3D)
Great Aletsch	07.02.2005	TM	2	153.04	24.65	LT05_L1TP_195028_20050207_20180130_01_T1_sr_band2	5,500	107 (SRTM-1), 108 (GLO-90), 109 (swissALTI3D)
Great Aletsch	10.02.2006	TM	2	153.75	25.81	LT05_L1TP_195028_20060210_20180311_01_T1_sr_band2	5,500	107 (SRTM-1), 109 (GLO-90, swissALTI3D)
Great Aletsch	22.02.2007	TM	2	153.49	29.98	LT05_L1TP_194028_20070222_20180118_01_T1_sr_band2	5,500	106 (SRTM-1, GLO-90),

								107 (swissALTI3D)
Great Aletsch	18.02.2009	TM	2	151.65	28.13	LT05_L1TP_195028_20090218_20180302_01_T2_sr_band2	5,500	109 (SRTM-1, swissALTI3D), 108 (GLO-90)
Great Aletsch	21.02.2010	TM	2	152.59	29.46	LT05_L1TP_195028_20100221_20161016_01_T1_sr_band2	5,500	108 (SRTM-1, swissALTI3D), 106 (GLO-90)
Great Aletsch	08.02.2011	TM	2	153.85	25.08	LT05_L1TP_195028_20110208_20161010_01_T1_sr_band2	5,500	109 (SRTM-1, GLO-90, swissALTI3D)
Great Aletsch	25.02.2014	OLI	3	154.88	31.67	LC08_L1TP_194028_20140225_20170425_01_T1_sr_band3	5,500	108 (SRTM-1, swissALTI3D), 107 (GLO-90)
Great Aletsch	19.02.2015	OLI	3	155.22	29.38	LC08_L1TP_195028_20150219_20170412_01_T1_sr_band3	5,500	107 (SRTM-1), 108 (GLO-90), 110 (swissALTI3D)
Great Aletsch	15.02.2016	OLI	3	155.68	27.95	LC08_L1TP_194028_20160215_20170329_01_T1_sr_band3	5,500	110 (SRTM-1), 109 (GLO-90), 111 (swissALTI3D)
Great Aletsch	20.02.2018	OLI	3	165.56	21,33	LC08_L1TP_194028_20180220_20180308_01_T1	5,500	92 (GLO-90)
Great Aletsch	22.02.2019	OLI	3	155.72	27.70	LC08_L1TP_195028_20190214_20190222_01_T1_sr_band3	5,500	113 (SRTM-1), 109 (GLO-90), 112 (swissALTI3D)
Baltoro	11.02.1992	TM	3	141.60	30.55	LT05_L1TP_148035_19920211_20170123_01_T1_sr_band2	5,500	42
Baltoro	22.02.1996	TM	3	135.05	31.43	LT05_L1TP_148035_19960222_20170105_01_T1_sr_band2	5,000	38
Baltoro	24.01.2000	ETM+	2	151.94	29.48	LE07_L1TP_148035_20000124_20170213_01_T1_B2	200	31
Baltoro	15.02.2011	TM	2	147.36	34.91	LT05_L1TP_148035_20110215_20161010_01_T1_sr_band2	5,000	30
Baltoro	10.02.2015	OLI	3	150.86	34.45	LC08_L1TP_148035_20150210_20170413_01_T1_sr_band3	4,500	29
Baltoro	29.02.2016	OLI	3	147.82	40.67	LC08_L1TP_148035_20160229_20170329_01_T1_sr_band3	5,000	16
Baltoro	02.02.2018	OLI	3	152.16	32.33	LC08_L1TP_148035_20180202_20180220_01_T1_sr_band3	5,000	29
Baltoro	08.02.2020	OLI	3	151.29	33.83	LC08_L1TP_148035_20200208_20200211_01_T1_sr_band3	5,000	28
Gulkana	13.03.1986	TM	2	157.84	21.25	LT05_L2SP_068015_19860313_20200917_02_T1	3,300 (West) / 2,700 (East)	42 (West) / 21 (East)
Gulkana	30.03.1989	TM	2	157.45	29.41	LT05_L2SP_067016_19890330_20200917_02_T1	3,300 / 3,000	20 / 10
Gulkana	19.03.1999	TM	2	160.07	25.25	LT05_L2SP_066016_19990319_20200908_02_T1	3,900 / 3,800	21 / 8
Gulkana	14.03.2009	TM	2	162.21	23.80	LT05_L1TP_066016_20090314_20160906_01_T1_sr_band2	5,500	22 / 8
Gulkana	04.03.2011	TM	2	162.93	19.74	LT05_L2SP_066016_20110304_20200823_02_T1	2,900 / 2,700	24 / 22
Gulkana	06.03.2014	OLI	3	165.73	17.11	LC08_L1TP_066016_20140224_20170306_01_T1_sr_band3	6,500	23 / 23
Gulkana	27.02.2015	OLI	3	165.49	18.12	LC08_L1TP_066016_20150227_20170227_01_T1_sr_band3	7,500	25 / 21
Gulkana	21.02.2016	OLI	3	165.60	15.81	LC08_L1TP_067016_20160221_20170224_01_T1_sr_band3	7,000	25 / 23

Gulkana	02.03.2017	OLI	3	165.54	19.48	LC08_L2SP_068016_20170302_20200905_02_T1	3,650 / 3,000	24 / 23
Gulkana	07.03.2018	OLI	3	165.56	21.33	LC08_L2SP_066016_20180307_20200901_02_T1	4,000 / 3,500	25 / 20
Gulkana	22.02.2019	OLI	3	165.54	16.27	LC08_L1TP_066016_20190222_2_20190308_01_T1_sr_band3	5,500	25 / 22
Gulkana	16.02.2020 and 25.02.2020	OLI	3	165.57	17.30	LC08_L1TP_066016_20200225_20200313_01_T1_sr_band3	6,000	52 / 47
Gulkana	06.03.2021	OLI	3	165.62	21.05	LC08_L2SP_067016_20210306_20210317_02_T1	4,400 / 3,000	25 / 23
South Cascade	02.02.1987	TM	2	148.87	18.90	LT05_L1TP_046026_19870202_20161003_01_T1_sr_band2	5,000	34
South Cascade	18.02.1993	TM	2	147.04	23.98	LT05_L1TP_046026_19930218_20160928_01_T1_sr_band2	5,000	32
South Cascade	05.02.1994	TM	2	148.49	19.79	LT05_L1TP_046026_19940205_20160927_01_T1_sr_band2	5,000	33
South Cascade	11.02.1996	TM	2	144.09	20.01	LT05_L1TP_046026_19960211_20160925_01_T1_sr_band2	5,000	29
South Cascade	22.02.1997	TM	2	147.53	25.73	LT05_L1TP_045026_19970222_20160924_01_T1_sr_band2	5,000	31
South Cascade	29.01.2000	ETM+	2	157.10	20.21	LE07_L1TP_046026_20000129_20161003_01_T1_B2	100	32
South Cascade	20.02.2002	TM	2	150.97	25.98	LT05_L1TP_045026_20020220_20160916_01_T1_sr_band2	5,000	32
South Cascade	07.02.2003	TM	2	151.18	21.32	LT05_L1TP_045026_20030207_20160916_01_T2_sr_band2	5,000	33
South Cascade	10.02.2004	TM	2	152.29	22.59	LT05_L1TP_045026_20040210_20160914_01_T2_sr_band2	5,000	33
South Cascade	15.02.2006	TM	2	154.72	25.25	LT05_L1TP_045026_20060215_20160911_01_T1_sr_band2	5,000	29
South Cascade	02.02.2007	TM	2	157.05	21.44	LT05_L1TP_045026_20070202_20160911_01_T1_sr_band2	5,000	31
South Cascade	07.02.2009	TM	2	154.31	22.46	LT05_L1TP_045026_20090207_20160906_01_T1_sr_band2	5,000	32
South Cascade	17.02.2010	TM	2	154.56	25.93	LT05_L1TP_046026_20100217_20160904_01_T1_sr_band2	5,000	32
South Cascade	20.02.2011	TM	2	154.07	26.82	LT05_L1TP_046026_20110220_20160901_01_T1_sr_band2	5,000	33
South Cascade	15.02.2015	OLI	3	157.11	25.79	LC08_L1TP_046026_20150215_20170301_01_T1_sr_band3	5,000	28
South Cascade	13.02.2017	OLI	3	157.28	25.30	LC08_L1TP_045026_20170213_20180201_01_T2_sr_band3	5,000	31
Sperry	28.02.1986	TM	2	147.03	27.79	LT05_L1TP_041026_19860228_20161004_01_T1_sr_band2	3,500	25
Sperry	19.02.2000	TM	2	149.88	25.04	LT05_L1TP_041026_20000219_20160918_01_T1_sr_band2	3,500	11
Sperry	27.02.2003	TM	2	149.10	28.04	LT05_L1TP_041026_20030227_20160916_01_T1_sr_band2	3,500	27
Sperry	19.02.2006	TM	2	154.37	26.61	LT05_L1TP_041026_20060219_20160911_01_T1_sr_band2	3,500	12
Sperry	25.02.2008	TM	2	153.74	28.54	LT05_L1TP_041026_20080225_20160906_01_T1_sr_band2	3,500	12
Sperry	25.02.2014	OLI	3	156.53	29.46	LC08_L1TP_041026_20140225_20170307_01_T1_sr_band3	3,500	17
Sperry	28.02.2015	OLI	3	156.08	30.42	LC08_L1TP_041026_20150228_20170301_01_T1_sr_band3	3,500	20

Table S2: DEMs used to simulate shadows on glaciers, including spatial resolution, acquisition date, and data source.

DEM	Investigated Glacier	Spatial resolution [m]	Acquisition date	Source
swissALTI3D	Great Aletsch	(downsampled from 2 m to 5 m)	2017-2018	https://www.swisstopo.admin.ch/en/geodata/height/alti3d.html
ArcticDEM	Gulkana	2	2009	https://www.pgc.umn.edu/data/arcticdem SETSM_WV01_20090616_10200100079A2600_1020010007 D06000_seg1_2m_v3.0.tif (used item: SETSM_~1.TIF)
SRTM-1	Great Aletsch, Baltoro, South Cascade, Sperry	~30 (1-Arc second)	2000	http://www.opentopography.org
SRTM-3	Great Aletsch, Baltoro	~90 (3-Arc seconds)	2000	http://www.opentopography.org
NASADEM	Great Aletsch, Baltoro	30	2000	http://www.opentopography.org
ALOS World 3D (AW3D30)	Great Aletsch, Baltoro	30	2006-2011	http://www.opentopography.org
Copernicus Global DEM (GLO-30)	Great Aletsch, Baltoro	30	2011-2015	http://www.opentopography.org
Copernicus Global DEM (GLO-90)	Great Aletsch, Baltoro	90	2011-2015	http://www.opentopography.org
Viewfinderpanoramas DEM (VFP)	Baltoro	90	2000 incl. void fill data with variable dates	http://viewfinderpanoramas.org/

Table S3: Prior and posterior distributions of the parameters in the hierarchical models of glacier elevation change Δh with year y using bearing lines (Eqs. 1-11).

Parameter	Prior	Posterior
		Median 2.5% 97.5% of HDI
α	Normal (mean = 0, sd = 2.5)	0.23 -0.14 0.61
β	Normal (mean = 0, sd = 2.5)	-0.31 -0.64 0.03
σ_α	Normal (mean = 0, sd = 2.5) T(0,)	0.43 0.22 0.90
σ_β	Normal (mean = 0, sd = 2.5) T(0,)	0.38 0.19 0.80
κ	Normal (mean = 0, sd = 2.5) T(0,)	0.55 0.53 0.57
ζ	LKJCholesky(1) on \mathbf{R}	0.74 -0.00 0.98

Notes: Priors refer to standardised input data pairs of Δh and y using a mean of zero and unit standard deviation. T(·, ·) indicates a truncation of the distribution at a lower or upper boundary. sd, standard deviation. Degrees of freedom are constant ($\nu = 3$) and have no posterior estimate.

Table S4: Prior and posterior distributions of the parameters in the hierarchical models of glacier elevation change Δh with year y using all data (within and outside the Landsat period) and only for data within the Landsat period, determined from reference DEMs and historical maps (Eqs. 1-11).

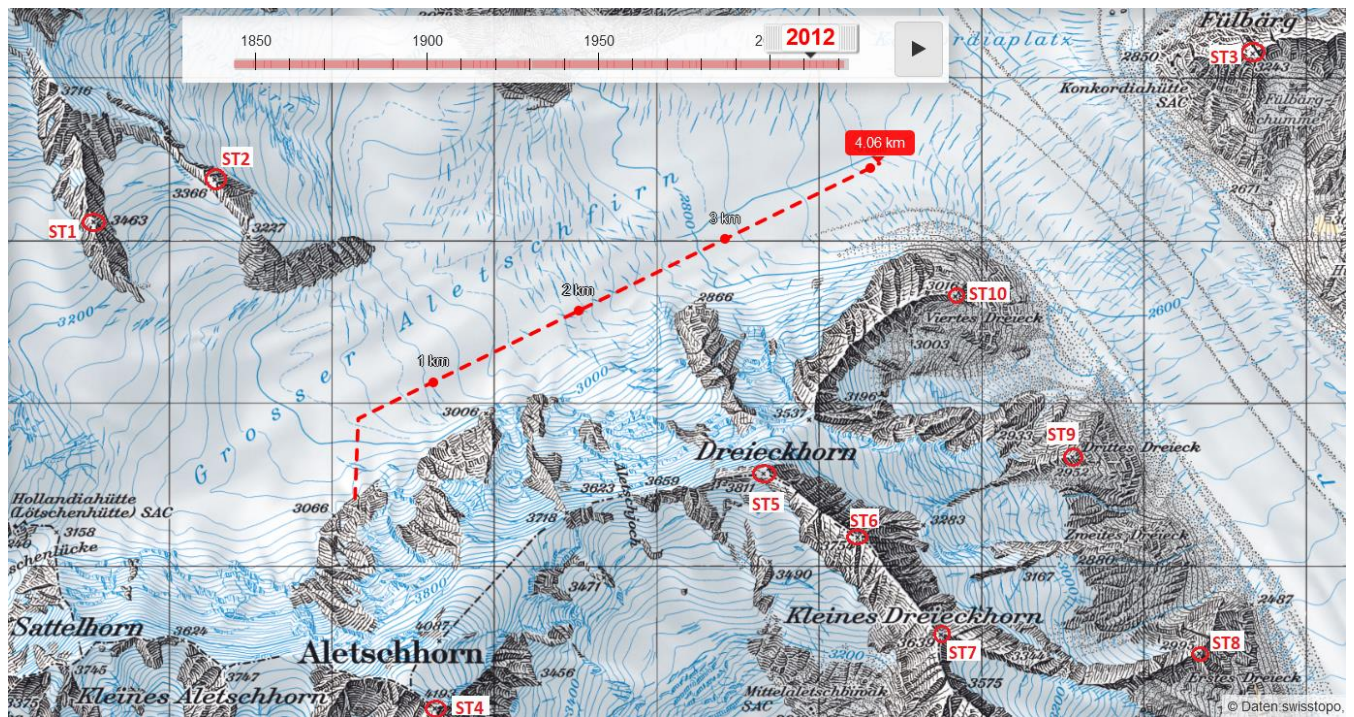
Parameter	Prior	Posterior for all available data	Posterior for data from the Landsat era only
		Median 2.5% 97.5% of HDI	Median 2.5% 97.5% of HDI
α	Normal (mean = 0, sd = 2.5)	0.17 -0.85 1.16	0.17 -0.99 1.32
β	Normal (mean = 0, sd = 2.5)	-0.48 -1.02 0.06	-0.32 -0.64 0.04
σ_α	Normal (mean = 0, sd = 2.5) T(0,)	1.03 0.45 2.42	1.19 0.52 2.69
σ_β	Normal (mean = 0, sd = 2.5) T(0,)	0.52 0.45 2.42	0.27 0.01 0.88
κ	Normal (mean = 0, sd = 2.5) T(0,)	0.26 0.18 0.37	0.21 0.12 0.34
ζ	LkjCholesky(1) on \mathbf{R}	0.44 -0.55 0.97	0.01 -0.87 0.88

Notes: Priors refer to standardised input data pairs of Δh and y using a mean of zero and unit standard deviation. T(·, ·) indicates a truncation of the distribution at a lower or upper boundary. sd, standard deviation. Degrees of freedom are constant ($\nu = 3$) and have no posterior estimate.

Table S5: Comparison of heights at stable terrain (ST) in Landeskarte over time and with different DEMs.

year	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9	ST10
1959	3465	3366	3242.6	4195	3810.7	3754	3641 (snow)	2994.8	2951.7	3016.2
1968	3466	3366	3242.6	4195	3810.7	3754	3641 (snow)	2994.8	2951.7	3016.2
1971	3466	3366	3242.6	4195	3810.7	3754	3641 (snow)	2994.8	2951.7	3016.2
1975	3466	3366	3242.6	4195	3810.7	3754	3641 (snow)	2994.8	2951.7	3016.2
1981	3463	3366	3242.6	4195	3810.7	3754	3639	2994.8	2951.8	3016.2
1987	3463	3366	3242.6	4195	3810.7	3754	3639	2994.8	2951.8	3016.2
1993	3463	3366	3242.6	4193	3810.7	3754	3639	2995	2952	3016
1999	3463	3366	3242.6	4193	3810.7	3754	3639	2995	2952	3016
2005	3463	3366	3242.6	4193	3810.7	3754	3639	2995	2952	3016
2011	3463	3366	3243	4193	3811	3754	3639	2995	2952	3016
2016	3463	3366	3243	4193	3811	3754	3639	2995	2952	3016
2020	3463	3366	3243	4194	3811	3756	3639	2995	2952	3016
swissALTI3D	3460.5	3364.4	3242.2	NA	3810.2	3754.95	3638.1	2995.98	2953.1	3020.9
GLO-90	3386.9	3277.9	3114.9	4133.2	3750.2	3694.3	3571.2	2858.1	2894.5	2956.98
GLO-30	3389.9	3314.8	3119.6	4144.4	3791.7	3702.8	3584.9	2903.5	2926.2	3003.4

Figure S1: Webpage with historical maps (Landeskarte) from the Bundesamt für Landestopografie KOGIS (Koordination, Geoinformation und Services, <https://www.swisstopo.admin.ch>)



Notes: Red circles (ST1-ST10) represent locations of stable terrains (ST) that were investigated and compared with heights in different DEMs to proof the quality of the historical maps. Red dots represent locations we used to validate our results of glacier elevation changes.