Mass Balance Freya Glacier 2015-16

Bernhard Hynek[1], Daniel Binder[1], Michele Citterio[2]

[1] Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Vienna

[2] Geological Survey of Denmark and Greenland (GEUS), Copenhagen

Technical Report. Supplement to the mass balance data 2015-16 published in*:*

Hynek, Bernhard; Weyss, Gernot; Binder, Daniel; Schöner, Wolfgang; Abermann, Jakob; Citterio, Michele (2014): Mass balance of Freya Glacier, Greenland since 2007/2008. Zentralanstalt für Meteorologie und Geodynamik, Wien, PANGAEA. https://doi.org/10.1594/PANGAEA.831035

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Summary

*The annual surface mass balance 2015/16 of Freya Glacier (5.3km², 2013) was measured by 11 new ablation stakes (drilled within the spring 2016 fieldwork), an automatic camera and an automatic weather station (AWS, near stake 6) with continuous measurement of surface height change. The glacierwide annual surface mass balance was calculated to **-540 +/-100 mm w.e.** which is 10% more negative than the average value since the start of monitoring in 2007/08. The equilibrium altitude line (**ELA**) was at **950m a.s.l.** and the accumulation area ratio (**AAR**) **15%.** The glacierwide interpretation of mass balance distribution is based on an orthofoto from 12.7.2016, aerial fotos from 11.08.2016 and the snowline retreat measured by the automatic camera. Winter mass balance is based on ~100 snow depth probings with a mean snow depth of 201cm and one bulk snow density measurement of 320kg/m³ within a snowpit next to the AWS. Overall winter mass balance 2015/16 was **650 +/-50 mm w.e.**, which is 15% below the 6 year average. The high correlation between winter and annual mass balance shows, that interannual mass balance variability is mainly driven by winter accumulation.*

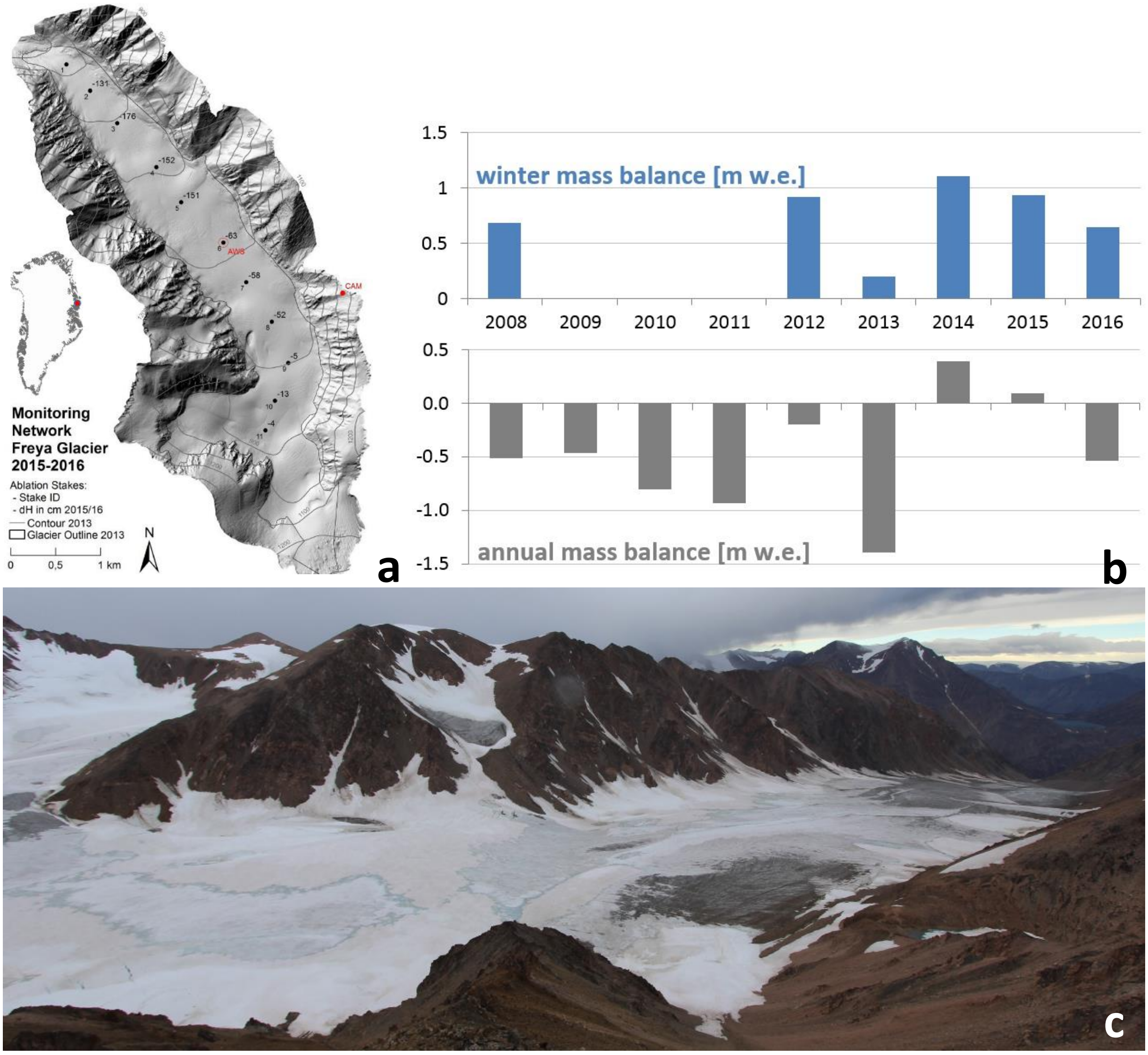


Figure: a) Map of monitoring network in 2015/16. b) Area averaged winter and annual surface mass balance of Freya Glacier since the beginning of the monitoring in 2007/08. c) Freya Glacier at the end of the summer 2016 on 29.8.2016 9:00 exposing firn layers that had been accumulated in the two previous positive mass balance years of 2014 and 2015. [webcam image]

Fieldwork Spring 2016

Fieldwork on Freya Glacier in spring 2016 took place between 22.4. and 10.5.2016 and was carried out by Daniel Binder (ZAMG), Bernhard Hynek (ZAMG), and Michele Citterio (GEUS). The purpose of the fieldwork was not only to measure the winter mass balance of the glacier, but also to install automatic measuremtent systems for a remote mass balance monitoring of Freya Glacier within the research project Glacio-Live and to change the ablation stake network from plastic to aluminium stakes that can be found and redrilled during spring, so that only one visit per year (in spring) is necessary. The following tasks were carried out during spring 2016 fieldwork:

- Winter mass balance measurements by snow depth probing (~100 points) and one snow density measurement.
- Installation of two automatic cameras for snow line monitoring on the ridge above Freya glacier powered by 3 solar panels and a wind mill and equiped with an Iridium Pilot Antenna for data transfer in near real time.
- Installation of a Promice-type (GEUS) automatic weather station (AWS) including snow height and ice ablation sensors to measure the surface mass and energy balance continuously. The termistor string for ice temperature measurements and the ablation hose was drilled only in spring 2017.
- Drilling of 11 aluminium stakes, each 6-8 meter long, to measure surface ablation.
- Recovery of sensors and datalogger from the old AWS, which had been burried by snow during the previous winter.

Winter mass balance

Snow probing took place on 22.4. (46 points), 7.5.(11 points, at stakes) and 10.5.2016 (46 points and snowpit). Between 22.4. and 10.5. there was snowfall and storm, but the amount of new snow was less than 10cm, so the values of different dates have been combined without adjustment to a measurement date of 10.5.2016.

The bulk density of the snow pack was measured in a snow pit next to the AWS (stake 6) on 10.5.2016. At the AWS there were 200 cm of winter snow accumulation with a mean density of 321 kg/m³ (SWE = 642 mm). Below the winter snow, there was 35cm of firn (density 507 kg/m³) and 9 cm of superimposed ice.

As snow depth point measurements vary along short distances by half a meter, we assume, that the snow probe penetrated through the firn layer of 2015 (and maybe 2014), so the higher values have benn corrected or deleted. Apart from totally unmeasured zones in the accumulation area that is the main source of uncertainty in the winter snow depth distribution on the glacier. So the mean snowdepth of 95 snow depth point measurements is 201cm, using a snow density of 321kg/m² this is a winter mass balance of 645mm w.e. A spatial interpolation of winter accumulation over the whole glacier yields a mean winter mass balance of 650 +/-50 mm. w.e.

Table: Values from the snow pit next to the AWS at stake 6 at an elevation of 688m a.s.l.

depth from [cm]	depth to [cm]	layer thickn. [cm]	weight total [g]	weight snow [g]	ρ [kg/m³]	swe [mm]	ρ mean [kg/m³]	swe sum [mm]	layer
0	20	19.0	314	107	229	46			
20	40	19.5	334	127	265	53			
40	60	20.0	336	129	262	52			
60	80	19.5	337	130	271	54			
80	100	19.5	333	126	263	53			
100	120	19.5	400	193	402	80			
120	140	20.0	375	168	341	68			
140	160	19.5	390	183	381	76			
160	180	20.0	407	200	407	81			
180	200	18.5	385	178	391	78	**321**	**642**	**snow**
200	235	19.5	450	243	507	177	**507**	**177**	**firn**
235	244				~850	72	**~850**	**72**	**SI ice**

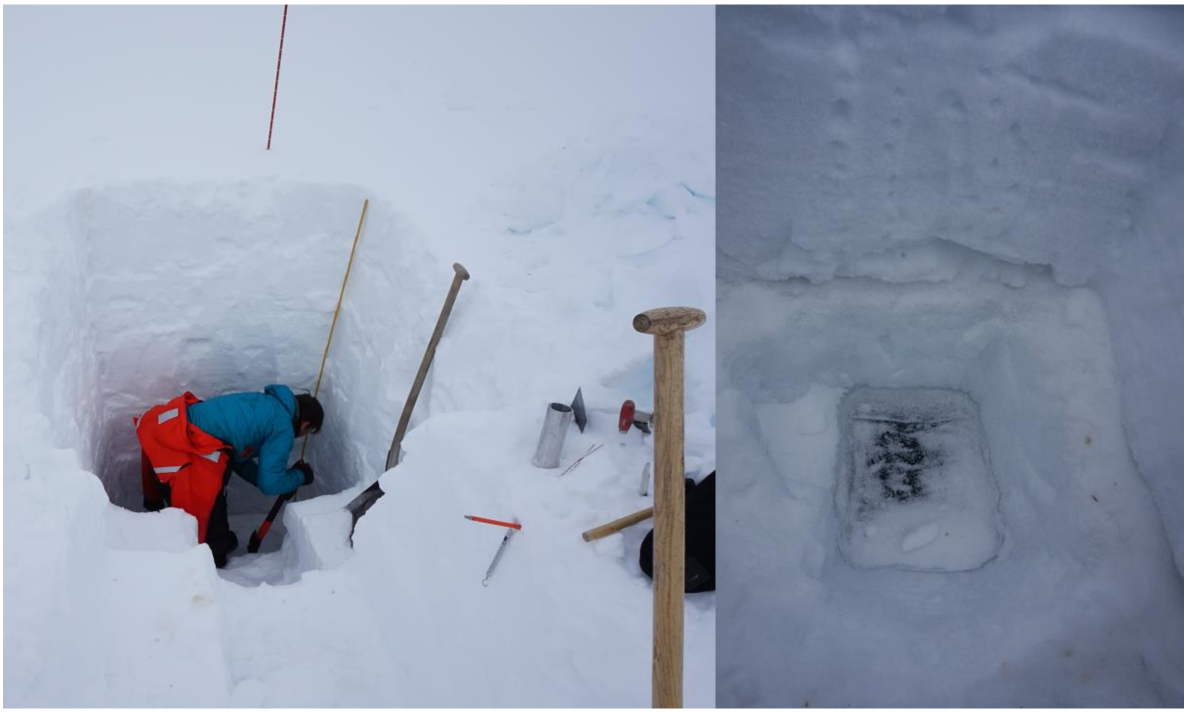


Figure: Snow density measurements in the snow pit next to the AWS at stake 6.

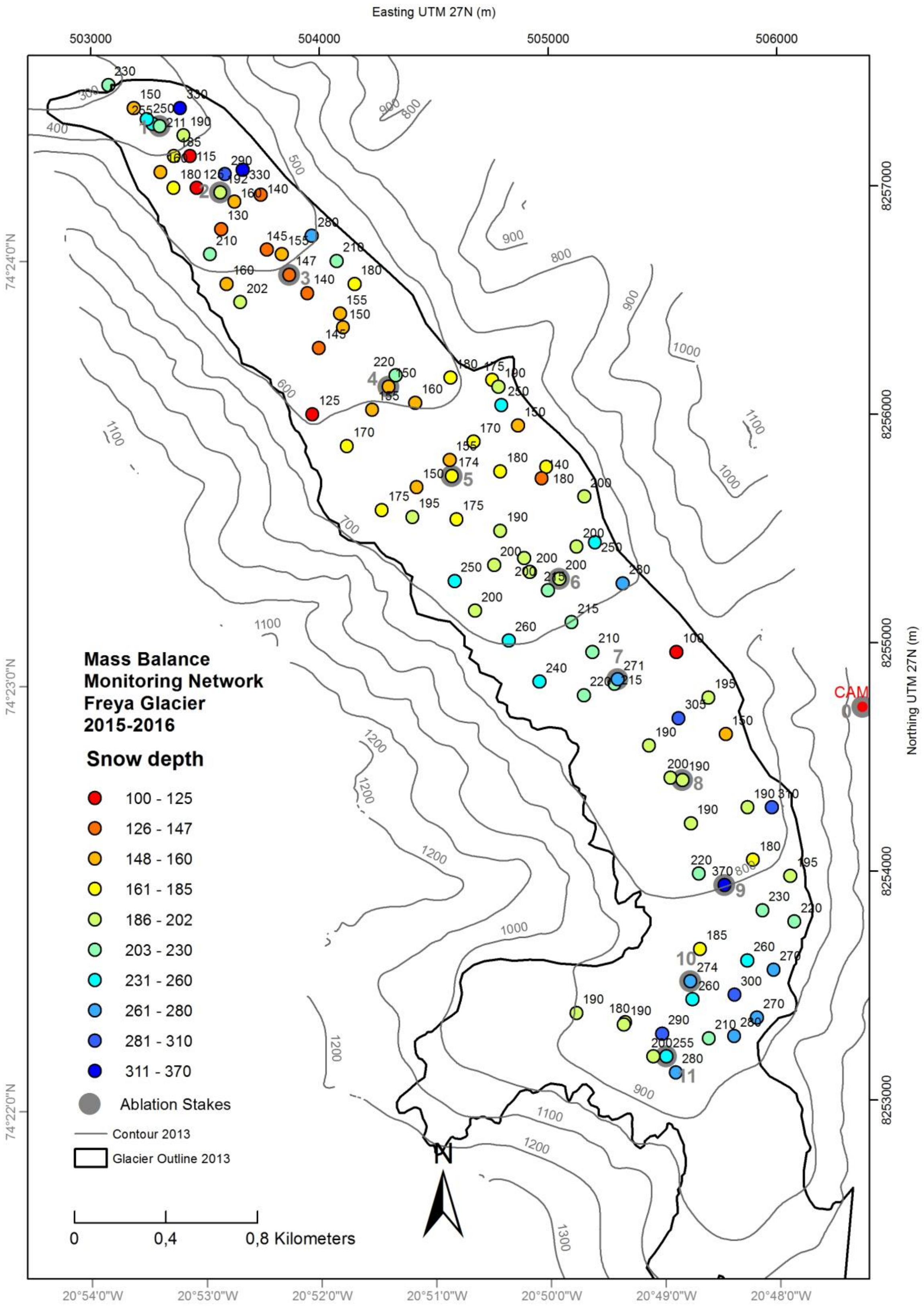


Figure: Snow depth point measurements on Freya Glacier in April/May 2016.

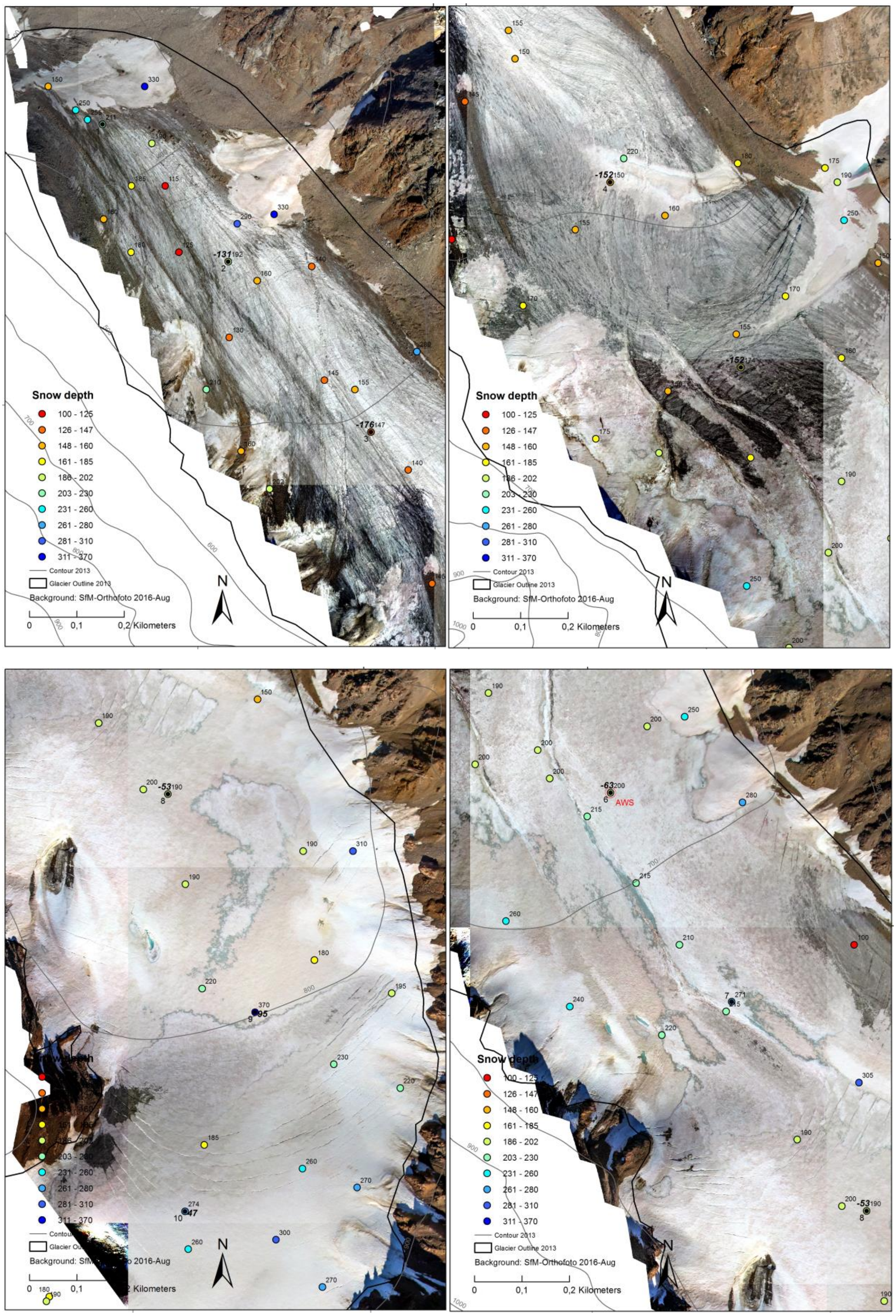


Figure: Snow depth point measurements from May 2016. In the background orthofoto of 11.8.2016.

Webcam-Installation for snow line monitoring

In May 2016 an automatic camera system has been installed on the ridge above Freya Glacier to monitor the daily snow cover and by that the spatial distribution of surface mass balance over the glacier. The system consists of two automatic cameras, 3 solar panels and a windmill for power generation, three 80 Ah lead batteries and an Iridium-Antenna for data transfer in near real time. In total this was an equipment of approx. 250 kg, that was carried up an elevation of 300 meters to be installed on a viewpoint on the northern ridge of the glacier at an elevation of 1053m a.s.l. One camera is directed downwards to cover most of the glaciers surface and the second camera is directed upwards to monitor the snowcover in the accumulation area. Unfortunately the upward camera had some electronic defect and did not deliver data in the first year. However this could be fixed in spring 2017, since then the camera is working properly. Online-Pictures of the webcams are here:

Downward camera: https://www.foto-webcam.eu/webcam/freya1/

Upward camera: https://www.foto-webcam.eu/webcam/freya2/

Table: Coordinates of the AWS and the Camera.

ID	UTM_x	UTM_y	Lat	Lon	Elevation
CAM	506376	8254720	74.3825	-20.7878	1052.8
AWS	505048	8255280	74.3875	-20.8320	688.1

Figure: Pictures of the installation of the webcams in spring 2016 (Fotos: B.Hynek).

Figures: Location of the automatic cameras on the ridge above Freya Glacier on an elevation of 1053m a.s.l. Upper picture: To the left is the windmill and on the right the Iridium Antenna for data transfer.The cameras are located below the Iridium Antenna.

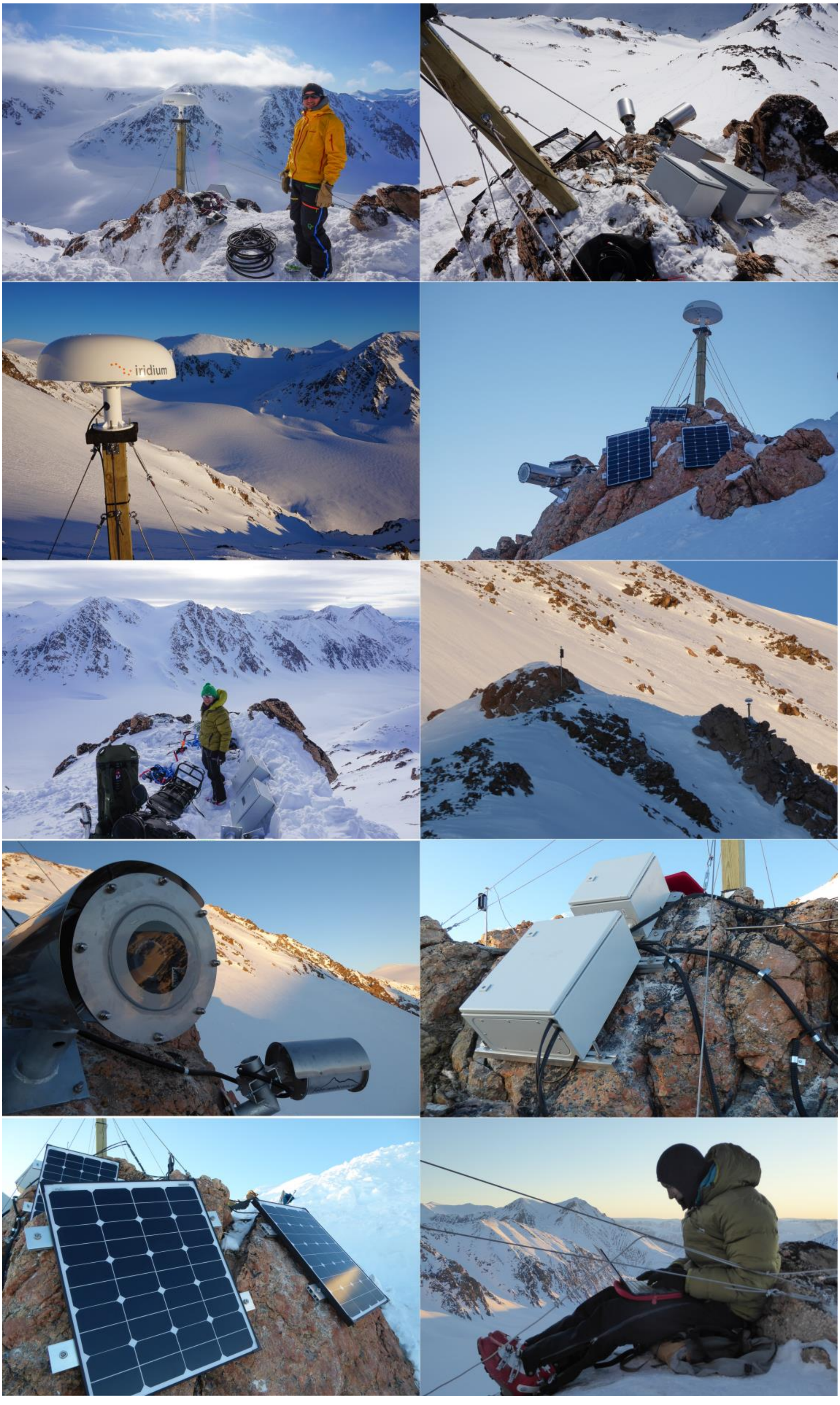


Figure: Fotos from the installation of the webcam station at an elevation of 1053m a.s.l.

Figure: Top: FreyaCam2 (left), and FreyaCam1 (right) Bottom: Panorama Picture generated with the two images. Almost the whole glacier surface is visible from the camera position.

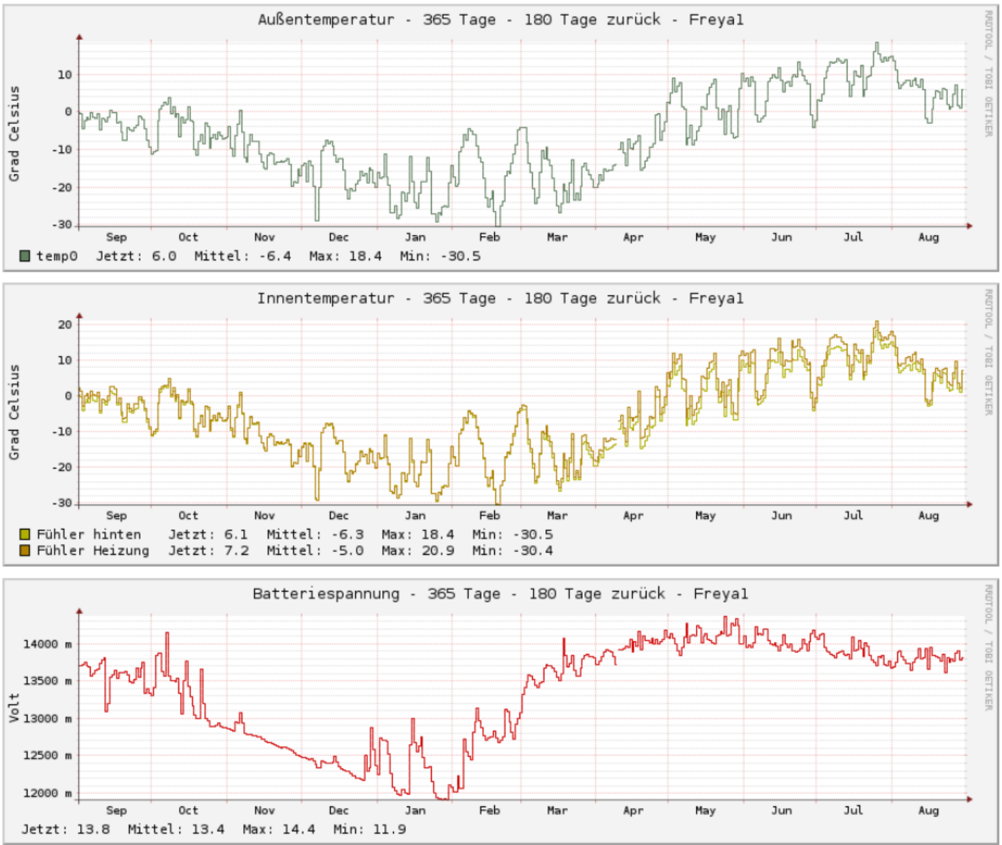


Figure: Temperature (outside and inside) and battery voltage at the camera station from Sept 2016 to Aug 2017. Windmill and solar panels provided enough energy to keep the station running during the Arctic winter.

Figure: Fotos from Camera Freya1 (downstream) during ablation season 2016. Freya2 (upstream) did not work properly in the first year. Mimimum snow cover was on 29.8.2016.

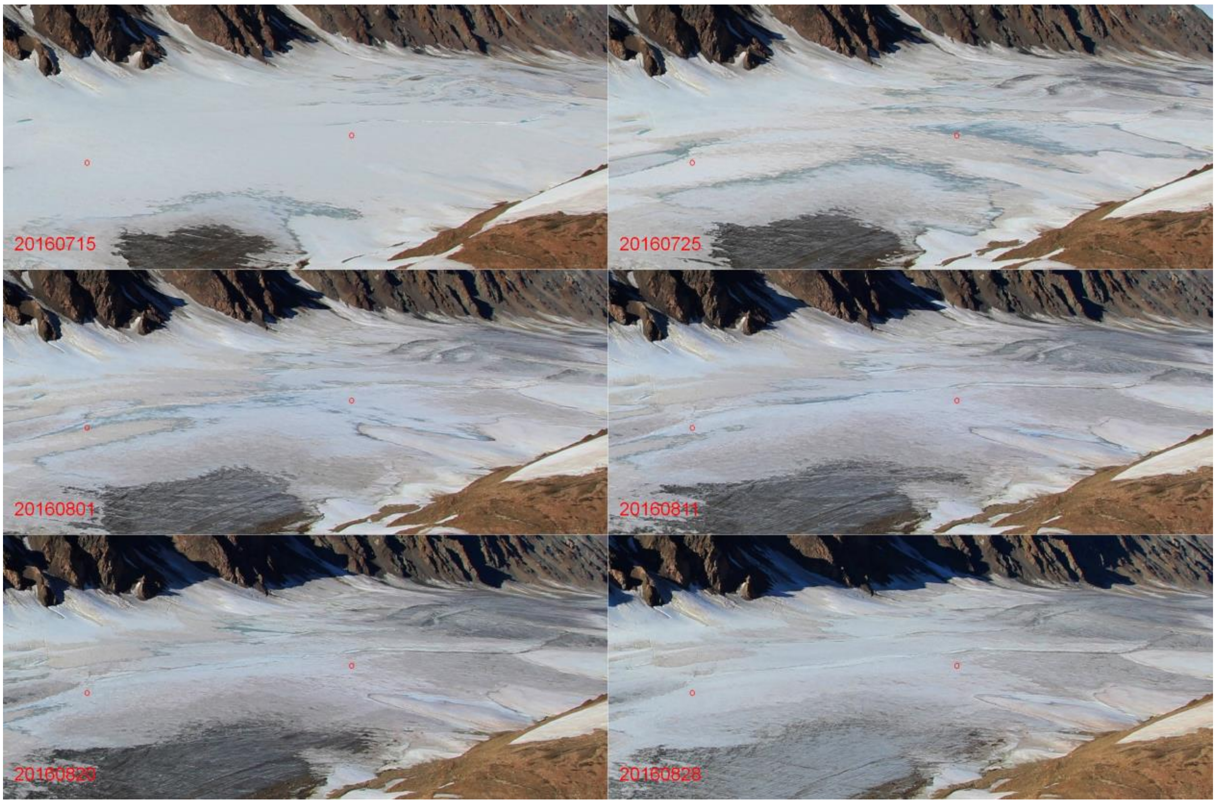


Figure: Details of Camera Freya1 during ablation season 2016, the left red dot is the approximate location of stake 7 and the right dot is stake 6 and AWS location. The images show showing complex stratigraphic patterns. Also refreezing processes do complicate surface classification into ice, firn (years 2014 and 2015) or winter snow. At the AWS there was an Albedo decrease from 0.8 to 0.3 between 17.7. and 25.7. The ablation at the AWS was 63 cm (measured with two ultrasonic devices) and at stake 7 it was 58cm.

Installation of a new automatic weather station (AWS)

In May 2016 an automatic weather station (AWS) was established on the surface of Freya Glacier at an elevation of 688m a.s.l. The weather station replaces the older station, that had been burried by winter snow during the last winter. The new station is a GEUS promice type station that measures all relevant variables to derive the surface energy balance and transfers all data via Iridium. Additionally two ultrasonic rangers for snow depth and snow/ice ablation are mounted on the floating station and on 3 extra aluminium poles, that had been drilled into the ice.

Figure: During the build up of the new AWS on Freya Glacier in May 2016.

Table: Data Table of the online transmitted data of the AWS. Data are transmitted every 6 hours and transmitted values are averaged values (4h means) or sample values from the last measurement, depnding on the quantity. In case of low battery power data are transmitted only once a day.

	quantity	unit	numeric		quantity	unit	numeric
1	timestamp		10.01.2018 00:00	16	ice temperature 1	average (°C)	-5.583
2	seconds_since_1990	sec	884390400	17	ice temperature 2	average (°C)	-4.376
3	air pressure	average (hPa)	619.7	18	ice temperature 3	average (°C)	-4.447
4	air temperature	average (°C)	-18.51	19	ice temperature 4	average (°C)	-4.504
5	relative humidity	average (%)	52.91	20	ice temperature 5	average (°C)	-3.944
6	wind speed	average (m/S)	1.688	21	ice temperature 6	average (°C)	-4.392
7	wind direction	average (dir)	167.1	22	ice temperature 7	average (°C)	-4.611
8	shortwave radiation in	average (Vx10^-5)	-1.33	23	ice temperature 8	average (°C)	-5.102
9	short wave radiation out	average (Vx10^-5)	0.432	24	tilt x	average (vx10^-2)	-3.637
10	longwave radiation in	average (Vx10^-5)	-46.62	25	tilt y	average (vx10^-2)	2.88
11	longwave radiation out	average (Vx10^-5)	-18.81	26	latitude	sample (dec deg)	7422.72062
12	temperature rad sensor	average (°C)	-19.09	27	longitude	sample (dec deg)	2049.34199
13	snow height	sample (m)	1.847	28	altitude	sample (m)	677.1
14	surface height	sample (m)	1.175	29	currents	sample (mA)	132.7
15	ice height	sample (mv)	20.05	30	battery voltage	sample (V)	12.39

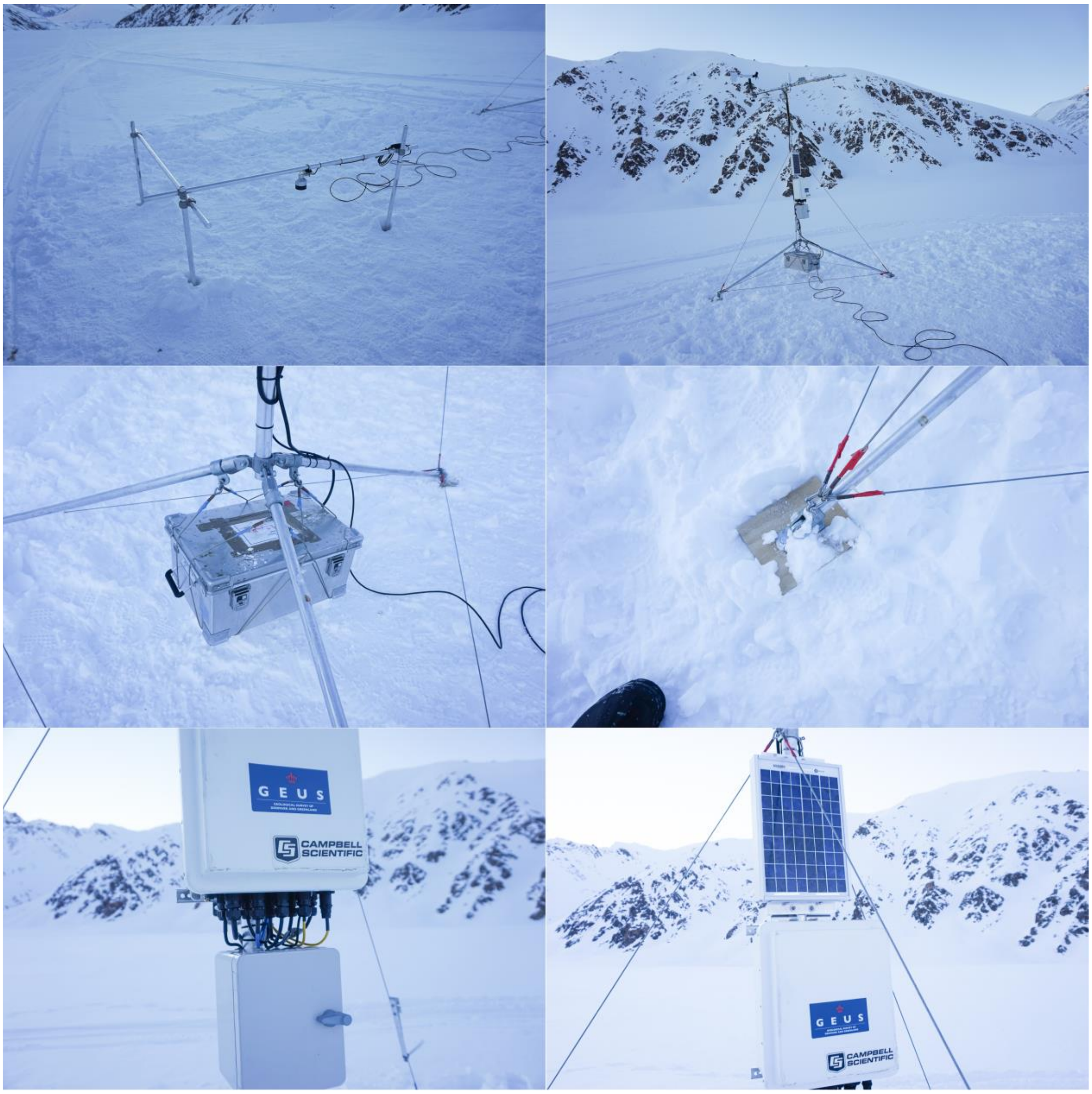
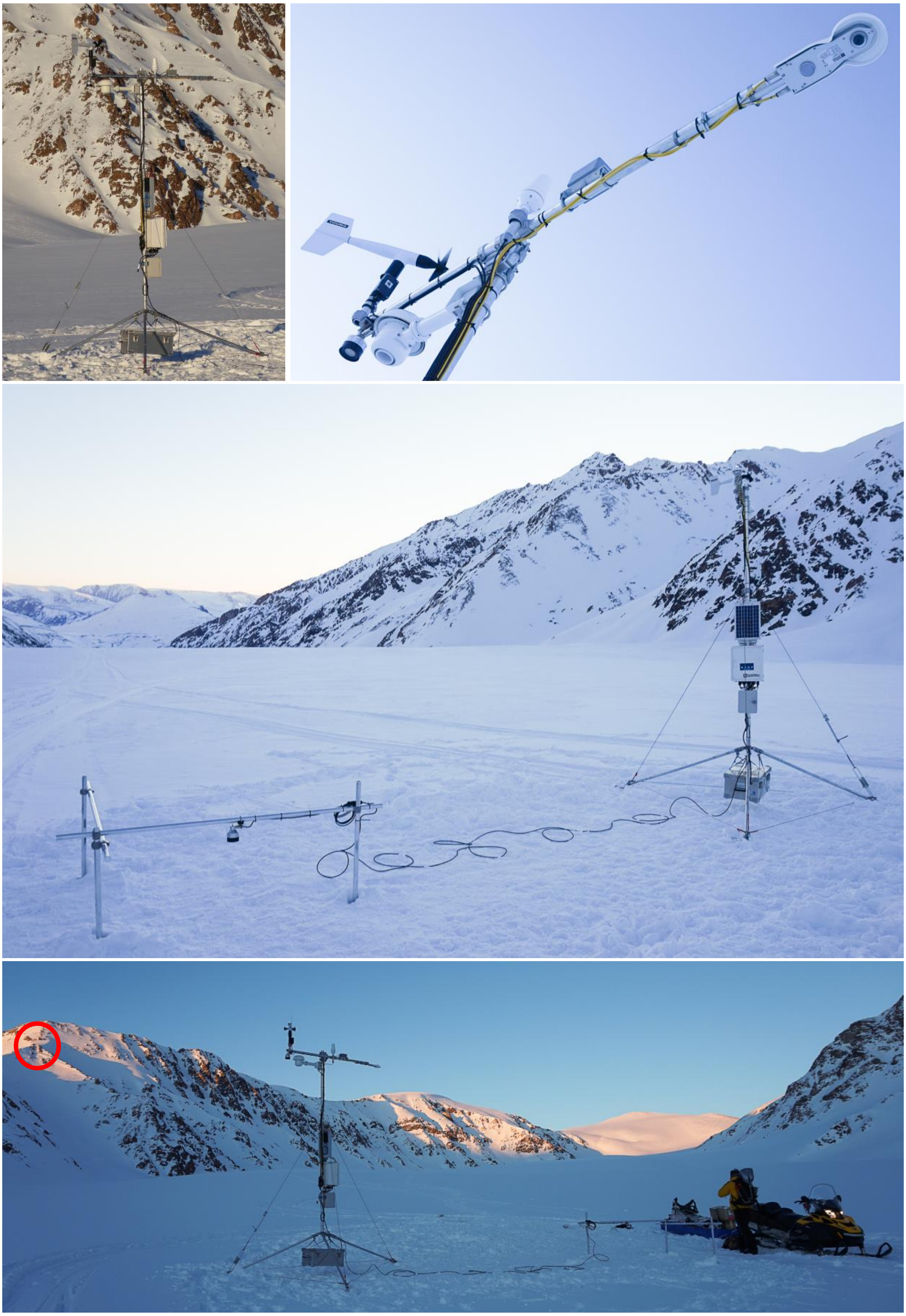


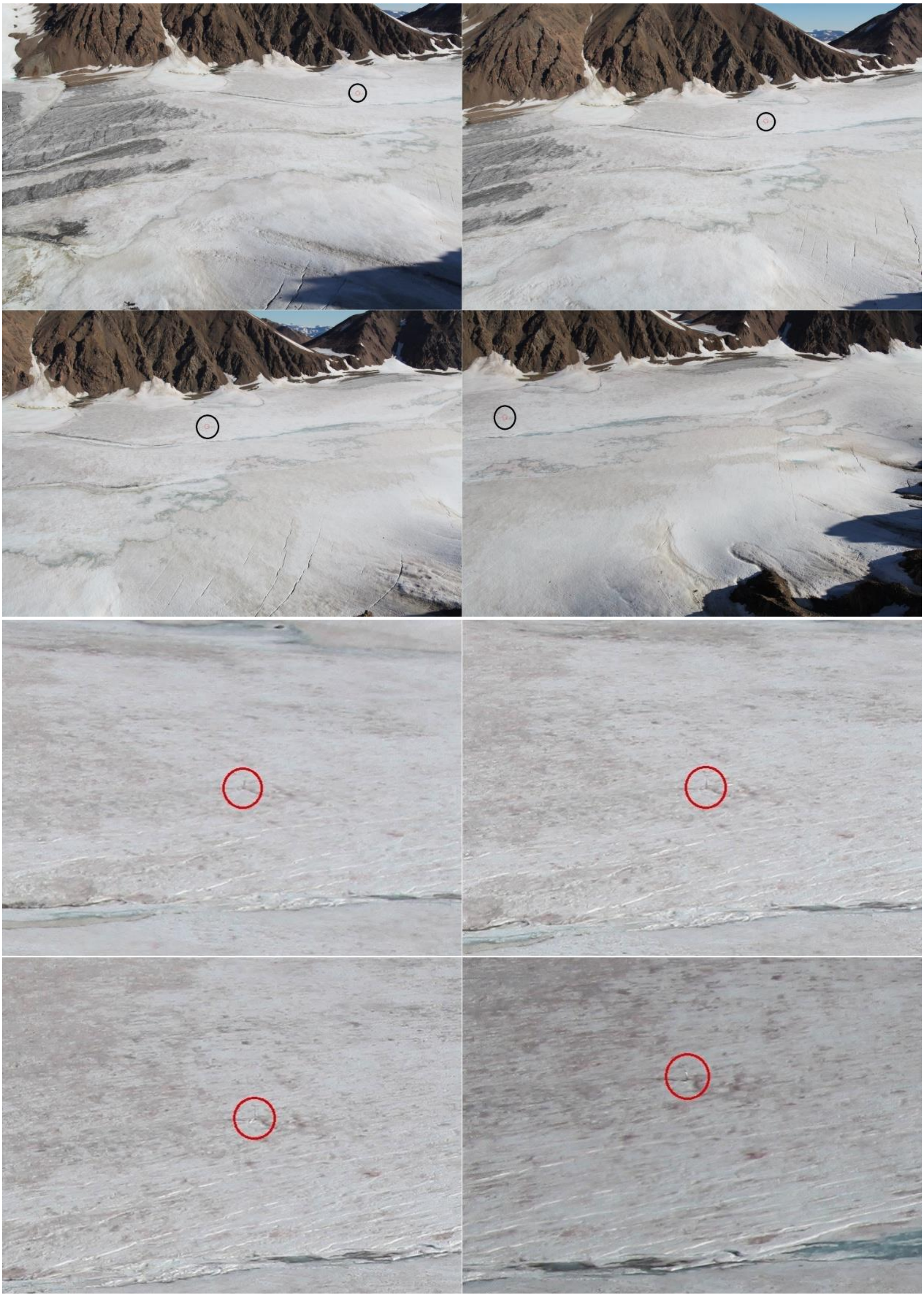
Figure: Details of the new AWS on Freya Glacier, Tall Guy.

Table: Manual measurements at the day of the AWS installation.

Manual measurements at the AWS in cm	07.05.2016
Temp/Hum height (bottom of casing - surface)	335
Sonic Ranger @ AWS height (membrane - surface)	340
Wind sensor height (center of propeller - surface)	385
Sonic Ranger @ Stakes height (membrane - surface)	58
Free length of stake - outer, with sonic ranger	86
Free length of stake -middle	76
Free length of stake - outer, without sonic ranger	80
Boom direction relative to magn North	204
Mast tilt in boom direction (+ if down)	-4
Mast tilt across boom (- if clockwise)	5
Height of surface irregularities	3
Snow height	200



Figures: The new AWS on Freya Glacier at on elevation of 688m a.s.l. The location of the automatic cameras is shown in the lowest picture.



Figures: Location of the AWS visible on fotos from the overflight on 2016-08-11. The station stands still in the firn area. To that date there had occurred already 40cm of firn ablation, until the end of the summer in 2016-08-29 firn ablation accumulates to 63cm. That firn had been built up in the previous two years.

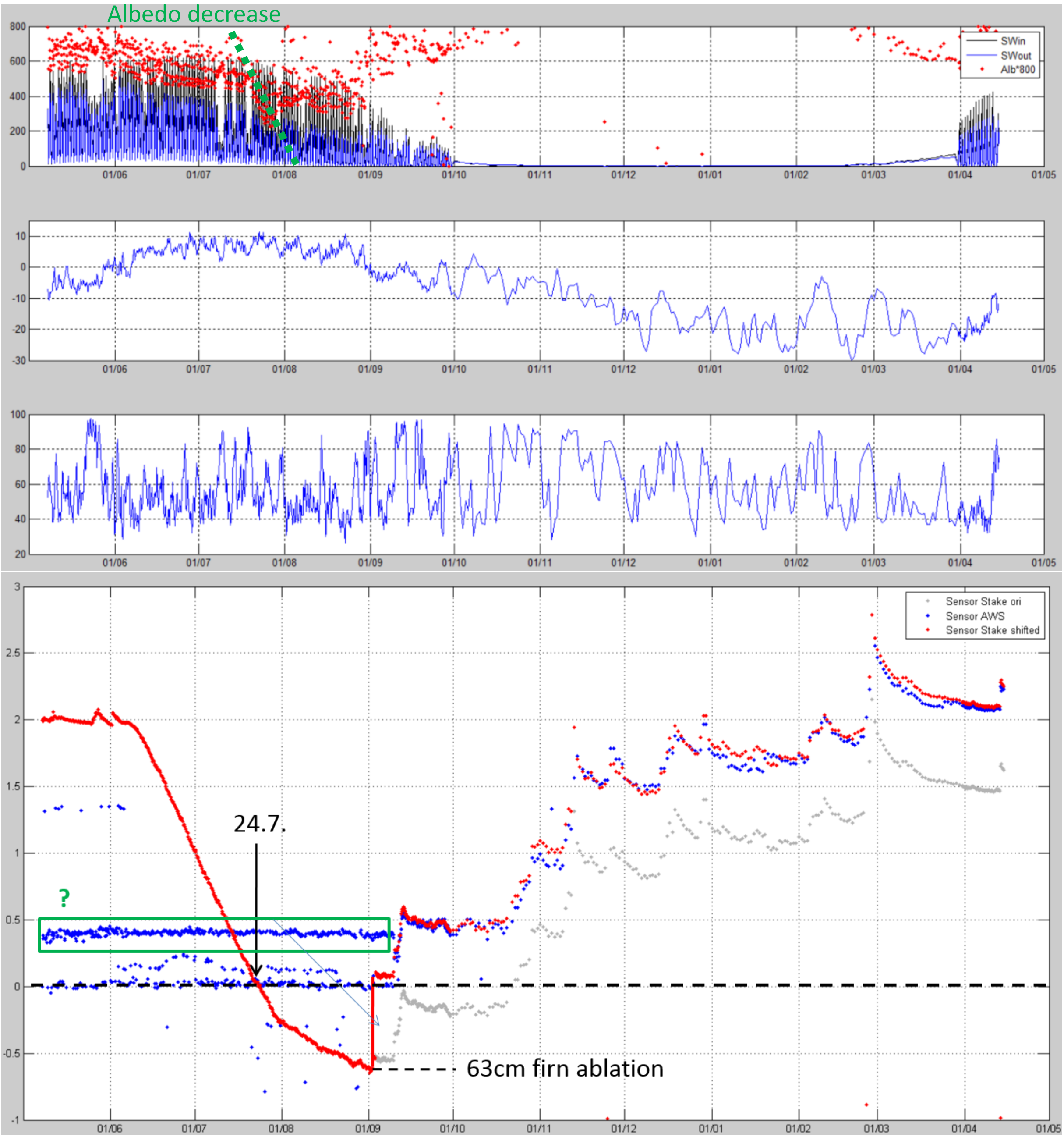


Figure: Data from the AWS at stake 6 from Mai 2016 to Mai 2017. From top to bottom: Shortwave radiation and albedo, temperature and humidity, surface ablation and accumulation measured by two different ultrasonic devices – one (red) mounted on a fixed pole to measure ice and firn ablation and one (blue) mounted on the AWS to measure only snow height.

Ablation stake network:

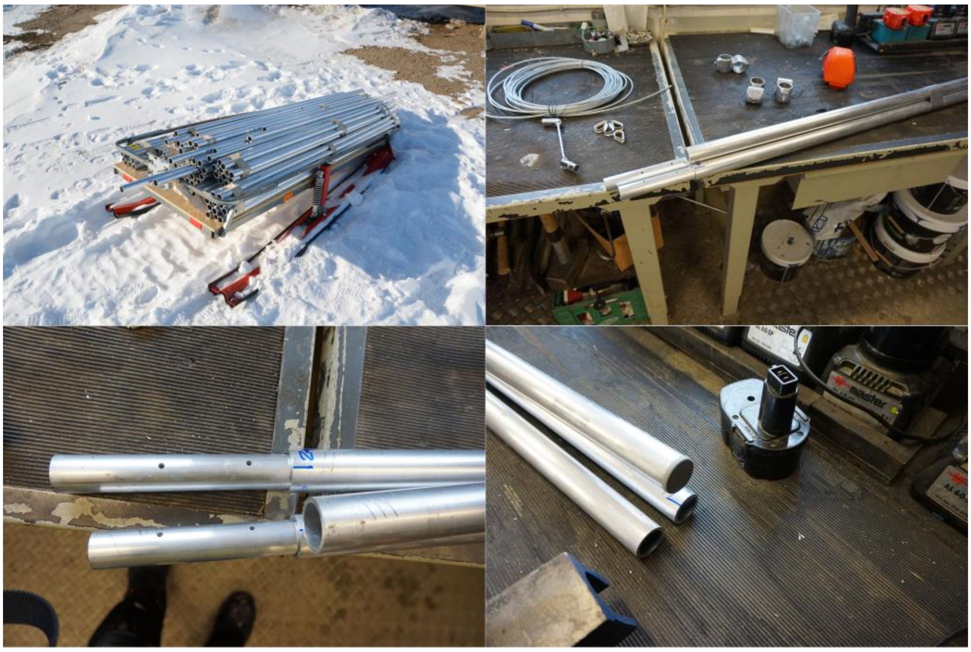


Figure: In May 2016 a total of 11 ablation stakes have been drilled into the ice. Stakes consist of 2m-segments. The lower stakes are 4 segments coupled to 8m long stakes, the upper ones are 3 segments coupled to 6m long stakes. At the bottom there are plastic caps to avoid thermal conduction and to enlarge the surface area. At every link the coupler pole is fixed with two rivets.

Table: Dimensions of the Aluminium Poles.

	Length [cm]	Outside diameter [mm]	Inside diameter [mm]	Wall thickness [mm]
poles	200.0	33	27	3
coupler	29.5	26		4

Table: Measurements at the ablation stakes in May 2016 and May 2017.

Stake ID	Stake Length [m]	Elev. [m a.s.l.]	snow depth 2016 [cm]	snow depth 2017 [cm]	dh to snow surf. 2016 [cm]	dh to snow surf. 2017 [cm]	in ice/firn 2016 [cm]	in ice/firn 2017 [cm]	ice/firn ablation 2016 [cm]	ice/firn density [10^3kg/m³]	mass balance 15/16 [mm w.e.]	comment
1	8	379	211	216	-50		639					*not found 2017*
2	8	438	192	153	-70	100	678	547	-131	900	-1179	
3	8	500	147	170	37	190	616	440	-176	900	-1584	
4	8	592	150	179	-73	50	723	571	-152	900	-1368	
5	8	646	174	195	-10	120	636	485	-151	900	-1359	
6-os	6	688	200	*210*	86	*139*	314	251	-63	650	-410	*dh 2017 est*
6-mid	6	688	200	*210*	76	*129*	324	261	-63	650	-410	*dh 2017 est*
6-ons	6	688	200	*210*	80	*133*	320	257	-63	650	-410	*dh 2017 est*
7	6	724	220	212	-5	61	385	327	-58	650	-377	*corrected*
8	6	776	190	211	50	81	360	308	-52	650	-338	
9	6	801	270	215	2	62	328	323	-5	600	-30	*corrected*
10	6	859	214	210	133	150	253	240	-13	600	-78	*corrected*
11	6	868	255	255	106	110	239	235	-4	600	-24	

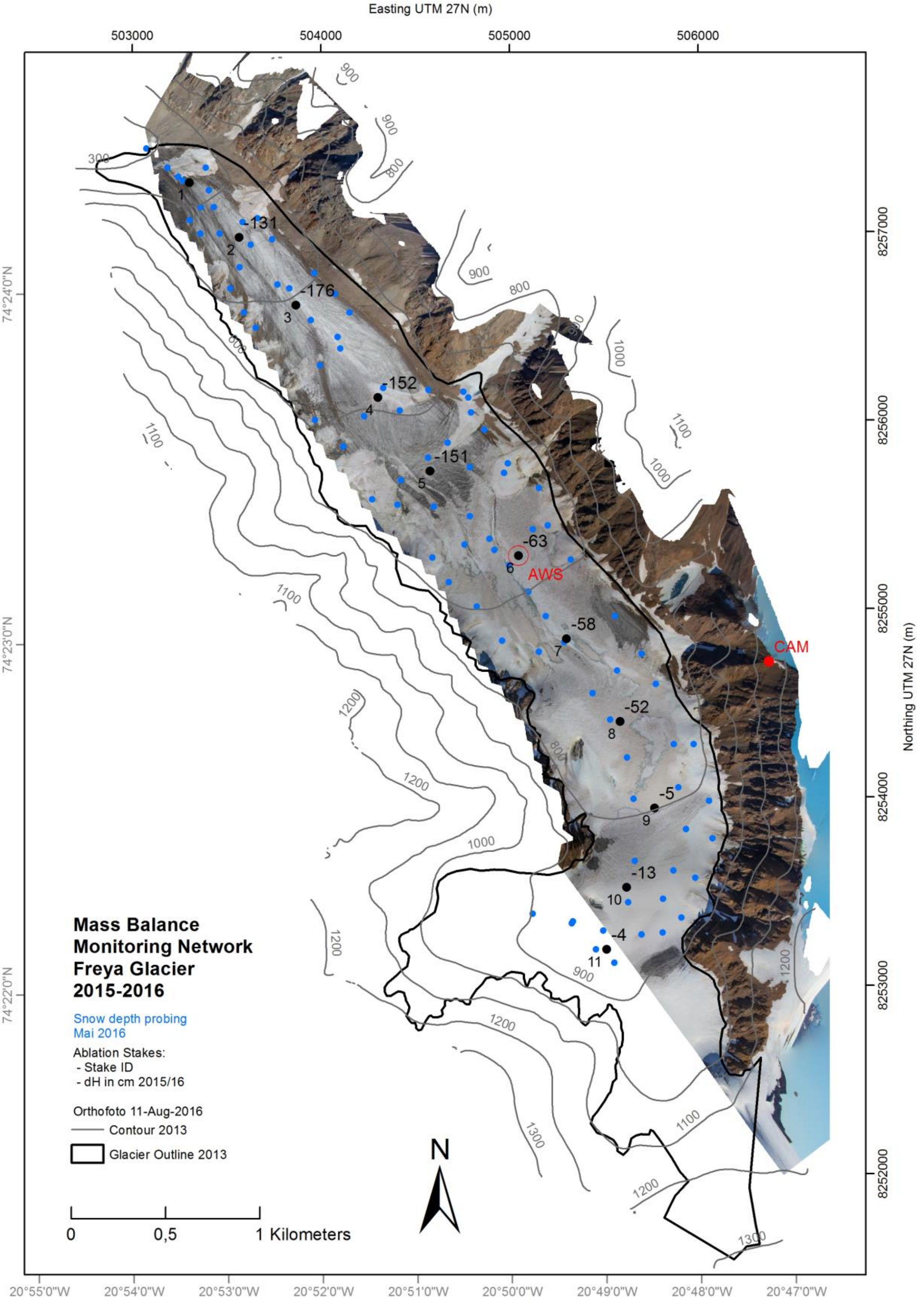


Figure: Map of the measurement points of mass balance 2016 with the Orthofoto of 11.8.2016 in the background.

Figure: Map of the measurement points of mass balance 2016 with the Orthofoto of July 12th 2016 in the background. The Orthofoto is a SPOT satellite acquisition. Contains data from Styrelsen for Dataforsyning og Effektivisering (SDFE), Denmarks Højdemodel, Januar 2016, downloaded from kortforsyningen.dk.

Overflight August 2016

On August 11th 2016 (close to the end of summer on August 29th 2016) the surface of Freya Glacier has been photographed within 44 fotos from an Airplane by Anders Anker Bjørk. The fotos were created with a CANON EOS MARK II, 24mm fixed zoom, 21 MPx. They have been matched and orthorectified using a structure from motion workflow and registered by using visible points from the 2013 sfm-model. The horizontal accuracy of the resulting orthofoto is approx. 5 meters. In the lower part of the glacier the bare ice surface is exposed, while the upper part is mainly covered by firn originating from the two last positive mass balance years of 2014 and 2015. Only a very small part of the glacier is still covered by what looks like winter snow, but this might also be a product of repeating refreezing events.

Figure: Thumbnails of 39 out of the 44 fotos from the plane overflight on August 11th 2016.

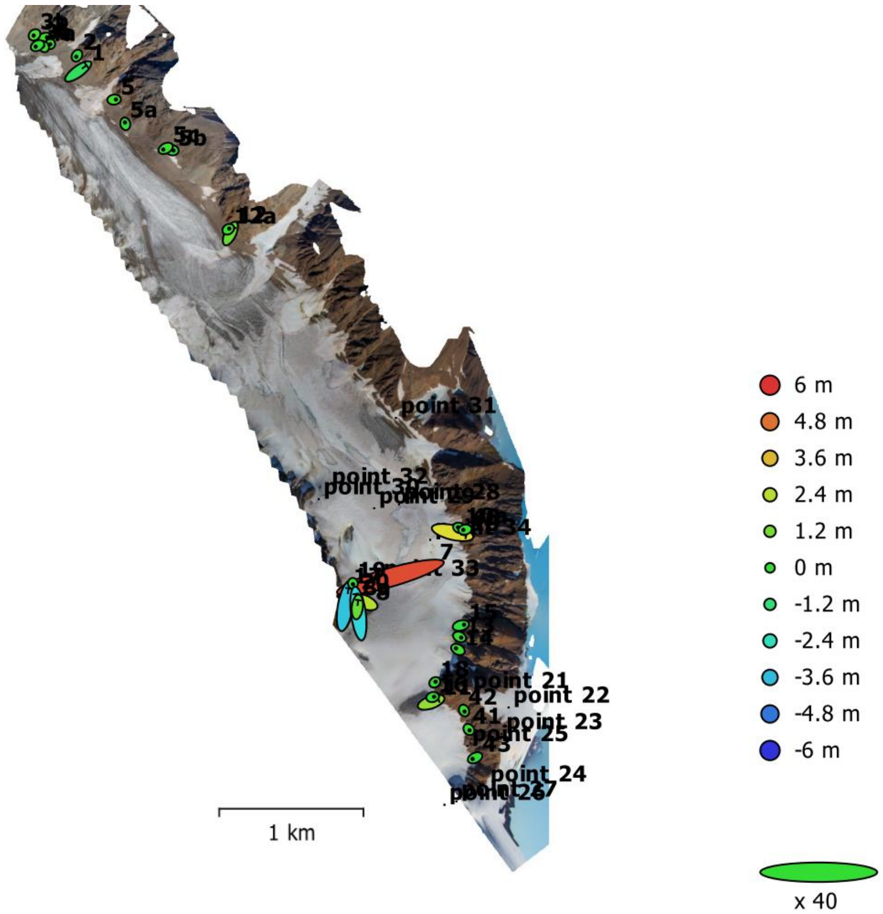


Figure: GCP locations and error estimates.

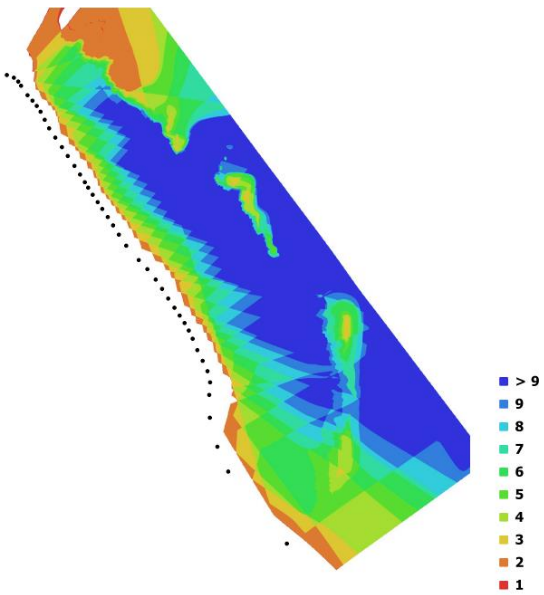


Figure: Left: Camera Locations and image overlap.
Right: Hillshade of the final DEM.

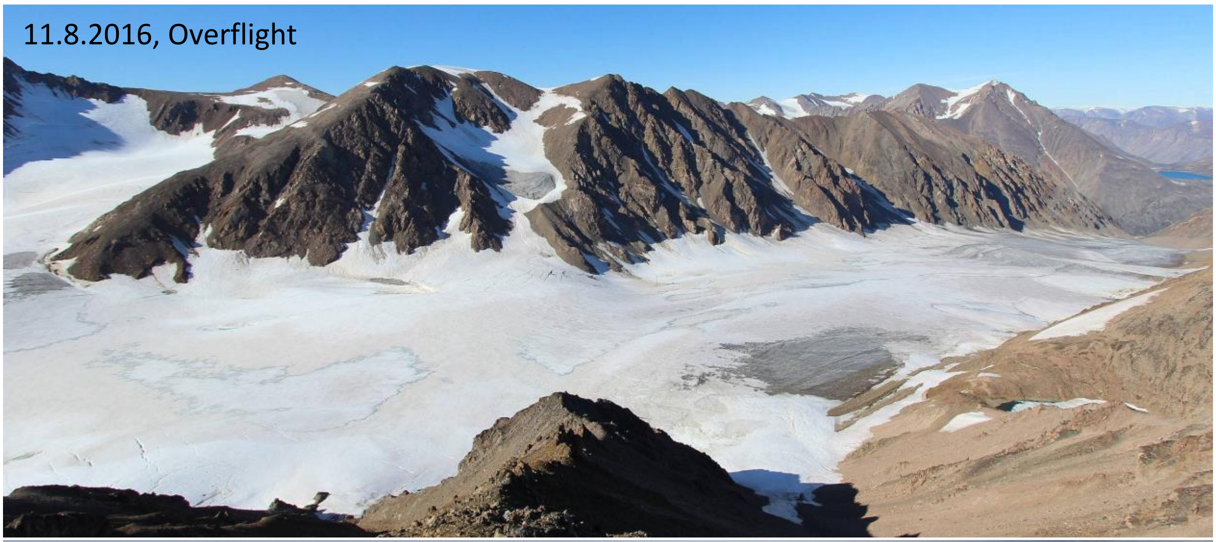
Table: Control Points error statistics.

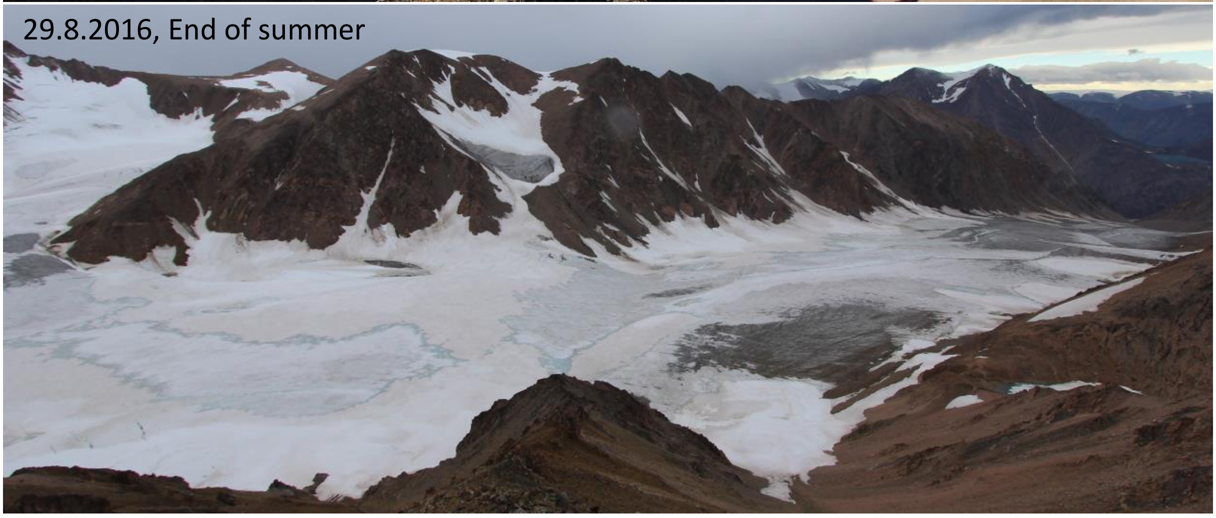
Label	X error (m)	Y error (m)	Z error (m)	Total (m)	Image (pix)
2	-0.234161	-0.366669	-0.147399	0.459352	0.760 (5)
3	0.675059	0.135353	0.17057	0.709309	0.120 (3)
4	-0.0156883	-0.0997228	-0.0278656	0.104725	0.973 (4)
5	0.609663	0.0633911	0.188712	0.641342	0.538 (8)
13	0.557822	-0.262256	0.114288	0.626901	1.046 (7)
14	-0.664808	0.360095	0.198567	0.781708	1.451 (7)
15	1.06542	0.276741	-0.244085	1.12751	0.950 (8)
16	0.489163	0.119914	-0.131473	0.520523	2.077 (6)
18	0.252096	0.193559	-0.013454	0.318118	1.189 (5)
19	0.0272606	-0.228134	0.0275935	0.231408	0.459 (3)
10a	-0.409246	0.184558	-0.193914	0.489027	1.102 (12)
40	-0.578014	-0.109591	0.125789	0.601609	0.727 (11)
41	0.236668	-0.281163	0.138667	0.392802	1.101 (6)
42	0.190356	-0.35778	-0.00473453	0.405296	0.442 (6)
43	-0.824338	-0.393572	-0.132001	0.92296	3.691 (5)
4a	-0.172537	0.253157	0.131984	0.333582	0.520 (3)
3a	-0.61354	-0.331084	-0.213782	0.729213	0.302 (3)
3b	-0.288653	-0.231343	0.449993	0.582524	0.056 (2)
5a	-0.100803	0.473117	-0.11912	0.498188	0.631 (9)
5b	0.417664	-0.0640948	-0.324423	0.532731	1.005 (13)
5c	-0.788303	-0.410352	0.188192	0.90842	1.177 (12)
12a	0.35423	0.234007	0.13144	0.444426	0.642 (15)
Total	**0.512067**	**0.272364**	**0.184065**	**0.608502**	**1.171**

Table: Check Points error statistics.

10	4.52755	-1.07439	2.98582	5.52884	1.482 (10)
11	2.4605	0.893047	1.63328	3.08532	1.710 (5)
12	1.04565	2.17216	0.938905	2.58712	0.525 (14)
7	-14.7891	-4.24166	5.49646	16.3377	0.620 (3)
8	-2.18698	0.905414	2.30107	3.30115	2.430 (4)
1	2.76081	2.00145	-0.784725	3.4991	1.617 (6)
17	1.04146	5.86424	-3.47927	6.89777	0.892 (3)
20	-0.839964	6.5211	-3.14591	7.28883	1.665 (4)
8a	0.266137	2.28783	0.846275	2.45381	0.677 (3)
Total	**5.38134**	**3.52193**	**2.81473**	**7.02036**	**1.357**


Figure: Resulting Orthofoto of
Freya Glacier, 2016-08-11
CAM
Orthofoto 11-Aug-2016
Glacier Outline 2013
0
0.5
1 Kilometers
N





Figures: Top:The glacier surface on 11.8.2016 during the overflight and on 29.8.2016, the day before the first snowfall. Fotos from the Automatic Camera.

Right: Orthofoto generated from the Automatic Camera picture above (11.8.2016). Background is a coloured hillshade to illustrate the non visible areas from the site of Cam 1. Visible feateures of the overflight Orthofoto of 2016-08-11 and the DEM 2013 have been used to orthorectify the camera images.

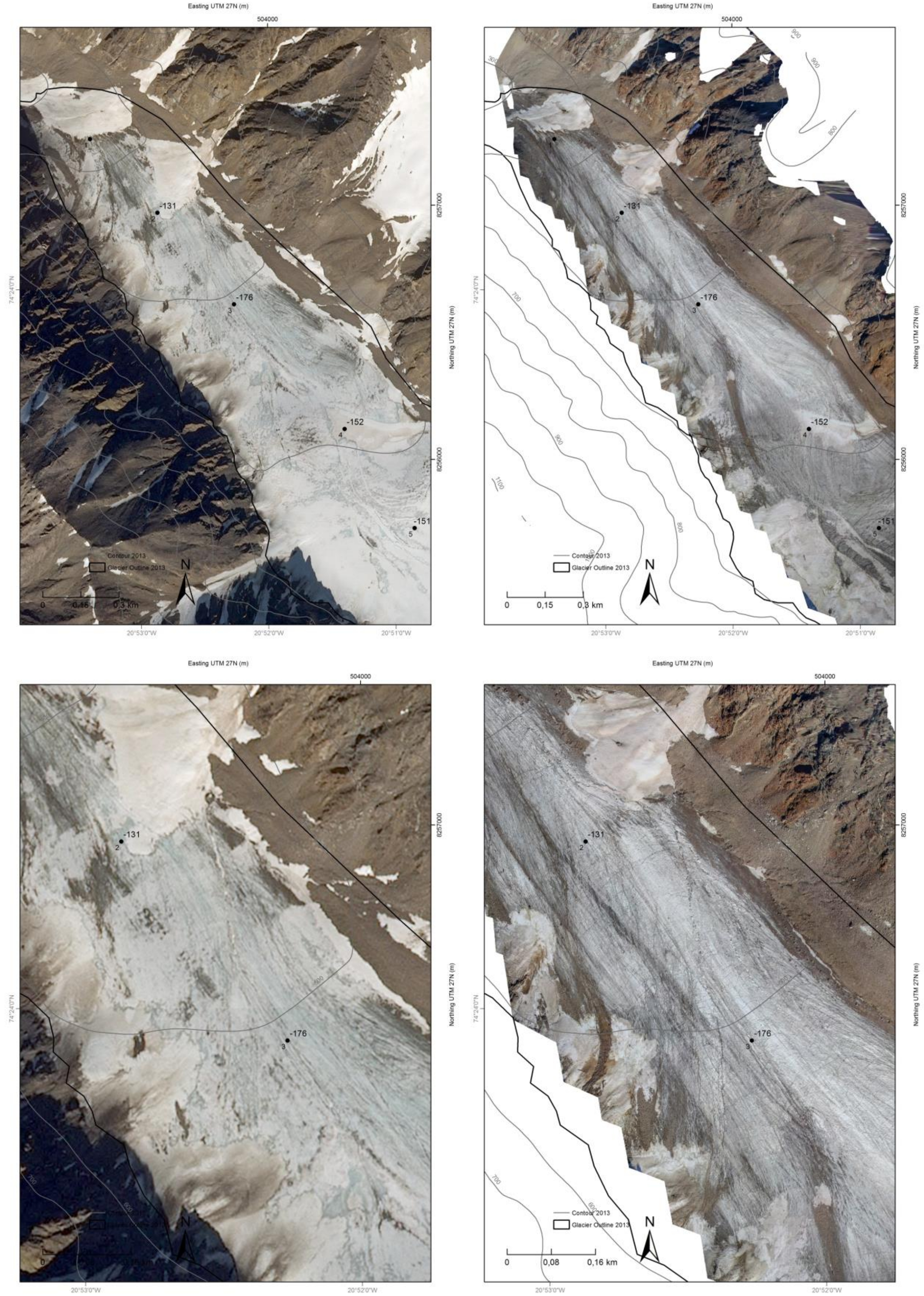


Figure: Comparison of the Orthofotos of July 12th 2016(left) and August 11th2016 (right).

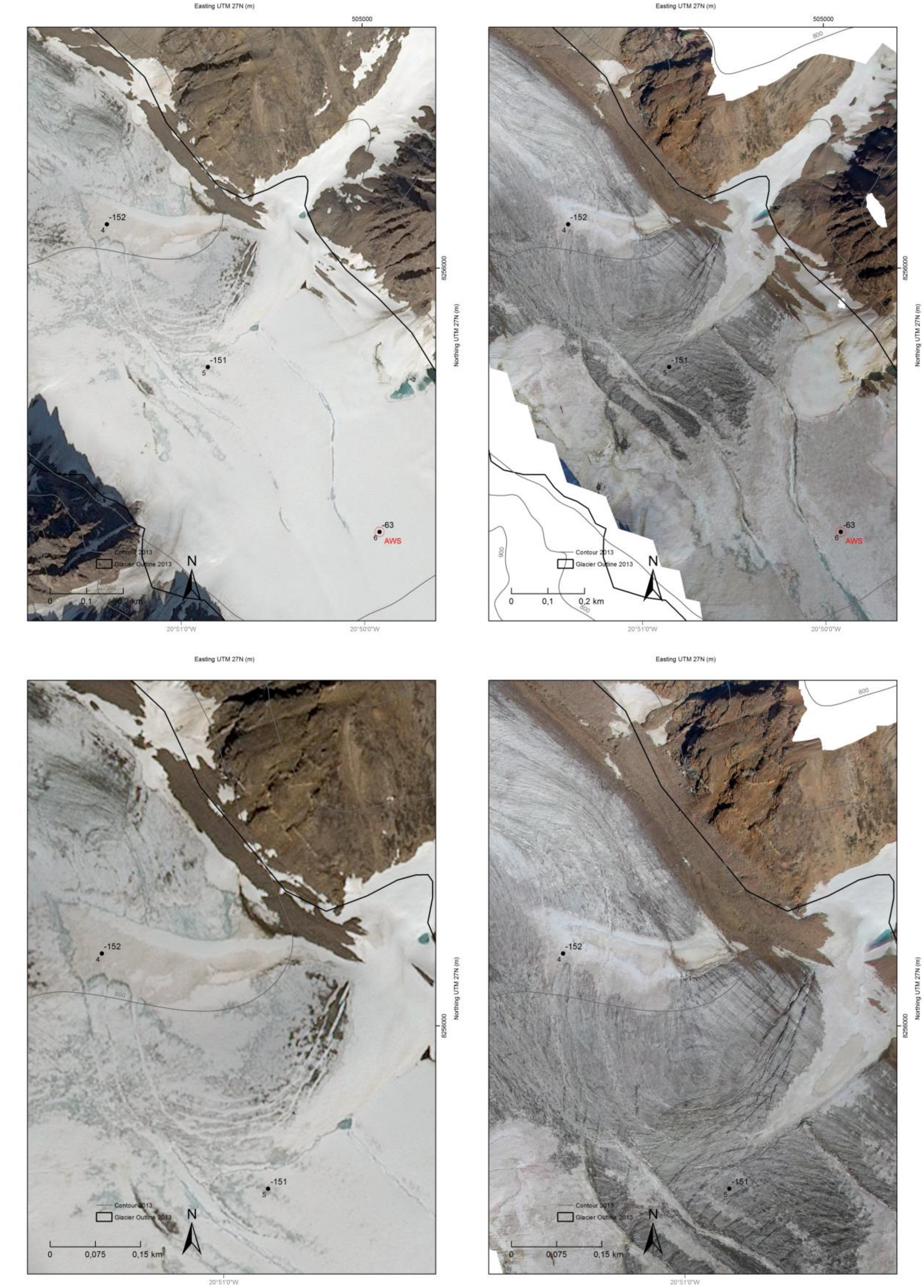


Figure: Comparison of the Orthofotos of July 12th 2016(left) and August 11th2016 (right).

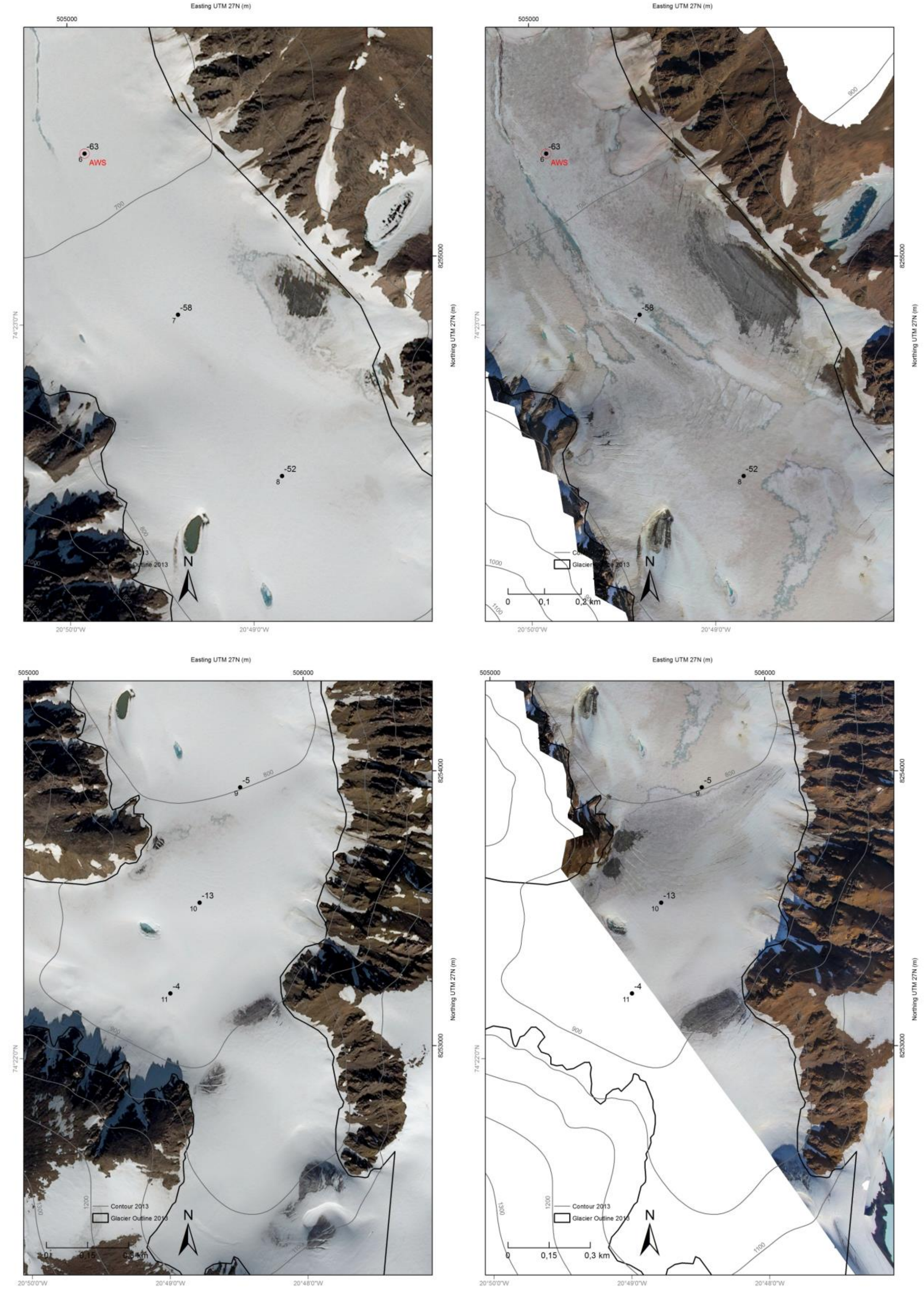


Figure: Comparison of the Orthofotos of July 12th 2016(left) and August 11th2016 (right).

Annual Mass Balance

The day of minimum snow cover was 29.8.2016. On that day it rained and in the evening was the first snowfall. The next snowfall was on 2.9.2016. Date of overflight and generation of the orthofoto was 11.8.2016, the surface was very similar to minimum snowcover. At the AWS we had 20-25cm ablation between 11.8. and 30.8.

Table: Ablation stake height change between Mai 2016 and Mai 2017. At least the upper 3 stakes had unrealistic readings, the values have been corrected according to visual mass balance seen on the fotos. There might have occurred vertical movement of the stakes.

ID	**Length** [m]	**East** [utm]	**North** [utm]	**Lat** [°]	**Lon** [°]	**Elev.** [m a.s.l.]	**dh** [cm]	**density** [kg/m³]	**mb 15/16** [mm w.e.]	**comment**
1	8	503302	8257260	74.4053	-20.8899	379	-			*not found*
2	8	503567	8256970	74.4027	-20.8812	438	-131	900	-1179	
3	8	503868	8256610	74.3995	-20.8712	500	-176	900	-1584	
4	8	504303	8256120	74.3951	-20.8567	592	-152	900	-1368	
5	8	504579	8255730	74.3915	-20.8475	646	-151	900	-1359	
6	6	505048	8255280	74.3875	-20.8320	688	-63	650	-410	
7	6	505303	8254840	74.3836	-20.8235	724	-58	650	-377	*corrected*
8	6	505587	8254400	74.3796	-20.8141	776	-52	650	-338	
9	6	505771	8253940	74.3755	-20.8080	801	-5	600	-30	*corrected*
10	6	505623	8253520	74.3717	-20.8130	859	-13	600	-78	*corrected*
11	6	505517	8253190	74.3688	-20.8166	868	-4	600	-24	

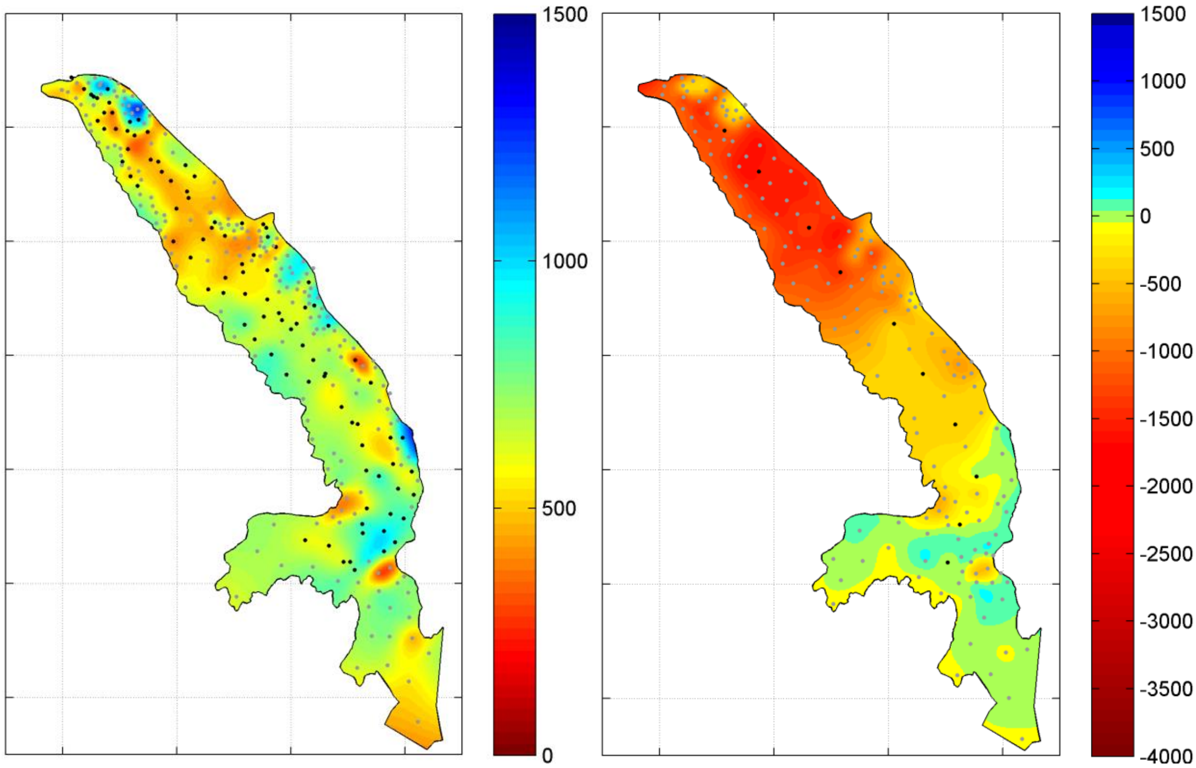


Figure: Winter (left) and annual (right) mass balance distribution on Freya Glacier 2015/16. The spatial distribution is generated by prescribing interpolation values (grey dots), which are based on previous mass balance distributions or best guess approximations. The estimated accuracy of the glacier wide annual mass balance is approximately 100 mm w.e.

Table: Mass Balance 2014/15 evaluated on elevation bands.

Date/ Time	Date/ Time end	Elev min [m a.s.l.]	Elev max [m a.s.l.]	SaZ [km^2]	BaZ [10^6kg]	baZ [kg/m^2]	BwZ [10^6 kg]	bwZ [kg/m^2]
2015	2016	1300	1400	0.001	0	-80	0	419
2015	2016	1200	1300	0.155	-6	-37	75	485
2015	2016	1100	1200	0.190	-3	-17	115	604
2015	2016	1000	1100	0.278	-10	-35	178	639
2015	2016	900	1000	0.633	-1	-1	449	709
2015	2016	800	900	0.804	-45	-56	583	725
2015	2016	700	800	1.064	-364	-342	719	676
2015	2016	600	700	1.073	-1009	-940	672	626
2015	2016	500	600	0.586	-839	-1432	320	546
2015	2016	400	500	0.370	-443	-1197	229	618
2015	2016	300	400	0.136	-127	-934	93	680
2015	2016	200	300	0.014	-19	-1390	8	612
2015	**2016**			**5.304**	**-2866**	**-540**	**3440**	**649**

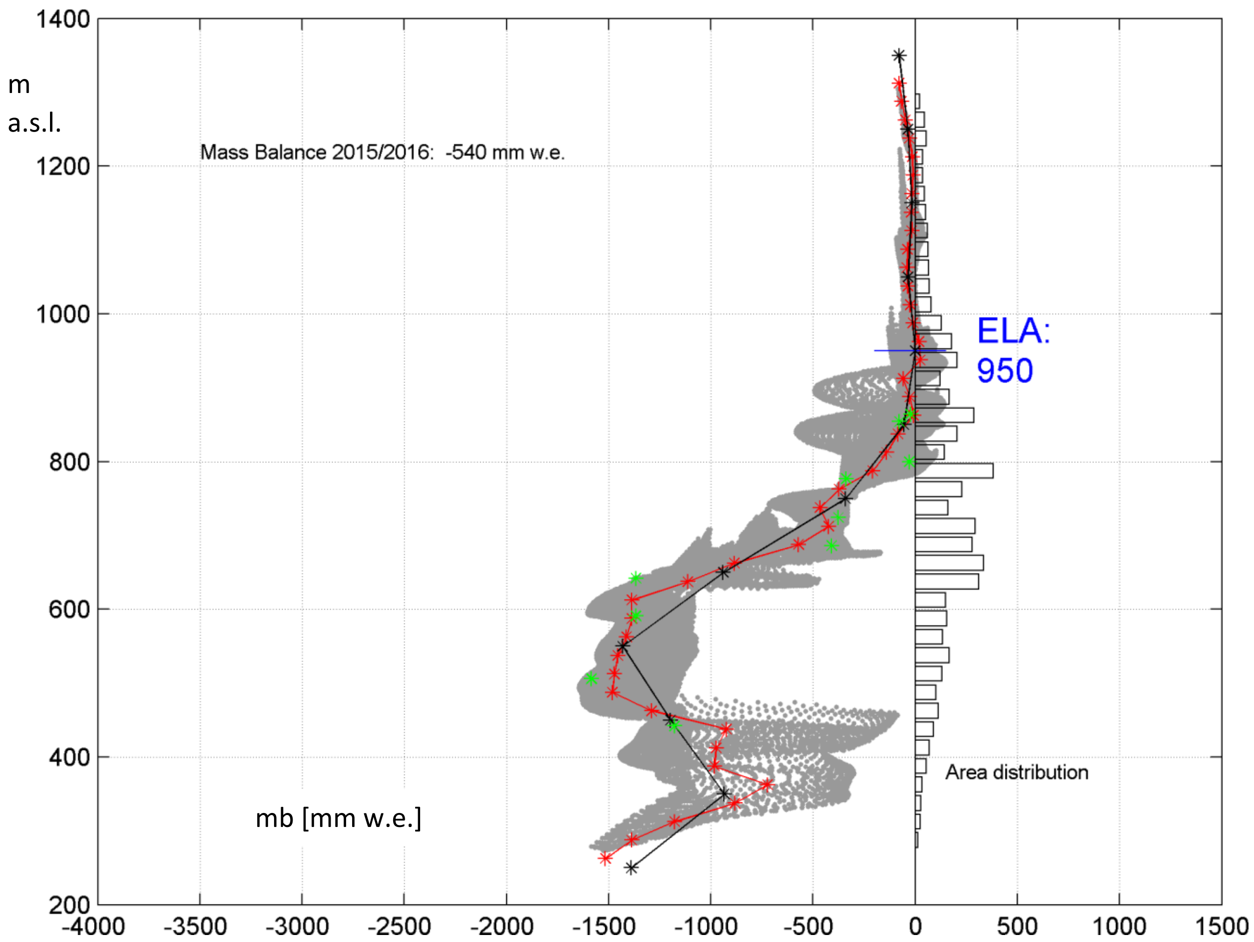


Figure: Mass balance distribution with elevation. Bars: Glacier area distribution. Green: Mb-point measurements. Grey: Grid values of interpolated mb raster. Black: mb mean values on 100m elevation bands. Red: mb mean values on 25m elevation bands.

Table: Mass balance periods at Freya Glacier:

MB Period	Date/Time start@annual balance	Date/Time end@annual balance	Date/Time start@winter balance	Date/Time end@winter balance
2007/2008	11.08.2007	23.08.2008	01.09.2007	12.05.2008
2008/2009	23.08.2008	24.08.2009		
2009/2010	24.08.2009	21.08.2010		
2010/2011	21.08.2010	23.08.2011		
2011/2012	23.08.2011	14.08.2012	20.09.2011	26.04.2012
2012/2013	14.08.2012	14.08.2013	25.08.2012	05.05.2013
2013/2014	14.08.2013	18.08.2014	14.08.2013	27.04.2014
2014/2015	18.08.2014	17.08.2015	01.09.2014	06.05.2015
2015/2016	17.08.2015	29.08.2016	17.08.2015	10.05.2016

Table: Mass Balance Results of Freya Glacier:

Year	Sc [km^2]	Bc [10^6kg]	bc [kg/m^2]	Sa [km^2]	Ba [10^6kg]	ba [kg/m^2]	S [km^2]	B [10^6kg]	b [kg/m^2]	Bw [10^6kg]	bw [kg/m^2]	ELA [m a.s.l.]	AAR
07/08	0.82	116	22	4.48	-2857	-539	5.30	-2741	-517	3682	694	1000	0.16
08/09	2.18	271	51	3.13	-2789	-526	5.30	-2518	-475			800	0.41
09/10	0.32	58	11	4.98	-4365	-823	5.30	-4307	-812			>1300	0.06
10/11	0.31	59	11	5.00	-5020	-946	5.30	-4961	-935			>1300	0.06
11/12	2.27	300	57	3.03	-1345	-254	5.30	-1044	-197	4856	916	750	0.43
12/13	0.16	20	4	5.15	-7413	-1398	5.30	-7393	-1394	1009	190	>1300	0.03
13/14	5.00	2102	396	0.30	-13	-2	5.30	2089	394	5853	1104	< 270	0.94
14/15	3.72	1342	253	1.59	-826	-156	5.30	516	97	4957	935	670	0.70
15/16	0.78	37	7	4.52	-2902	-547	5.30	-2865	-540	3440	649	950	0.15

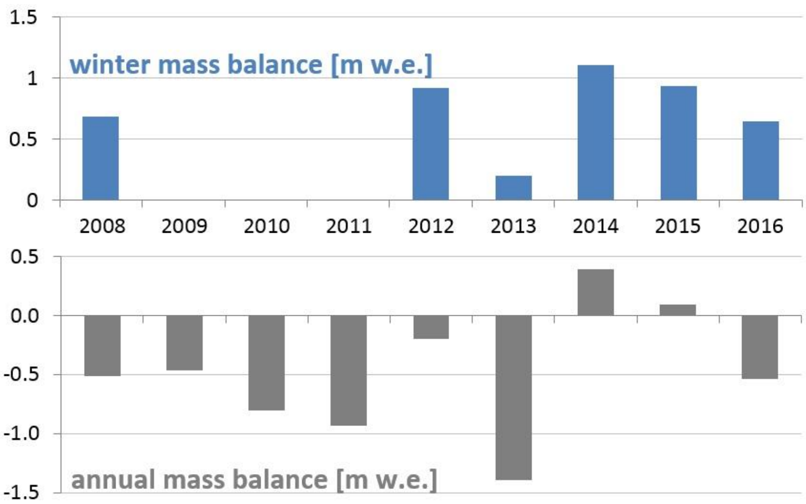


Figure: Time series of mean annual and winter mass balance of Freya Glacier in meters water equivalent.

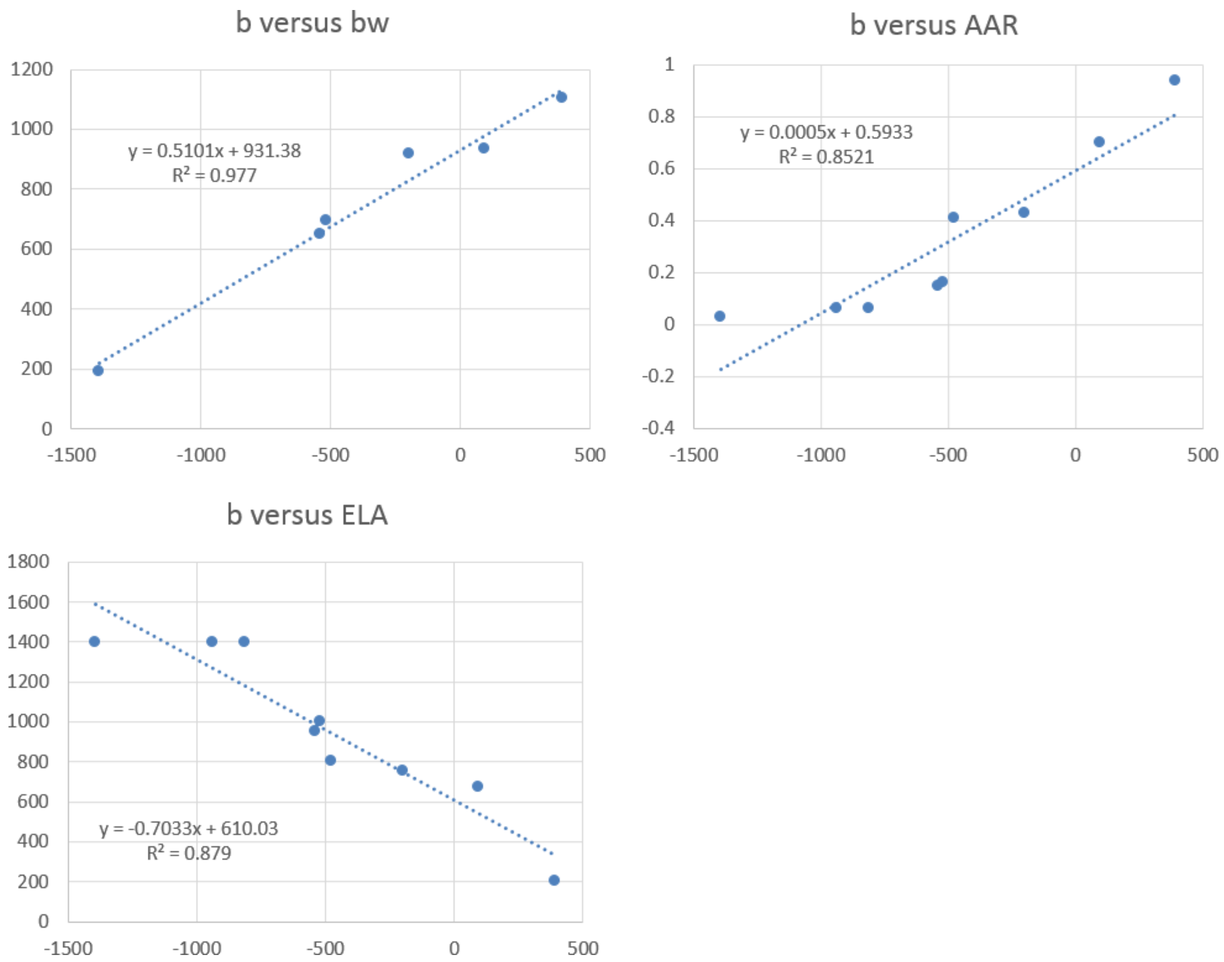
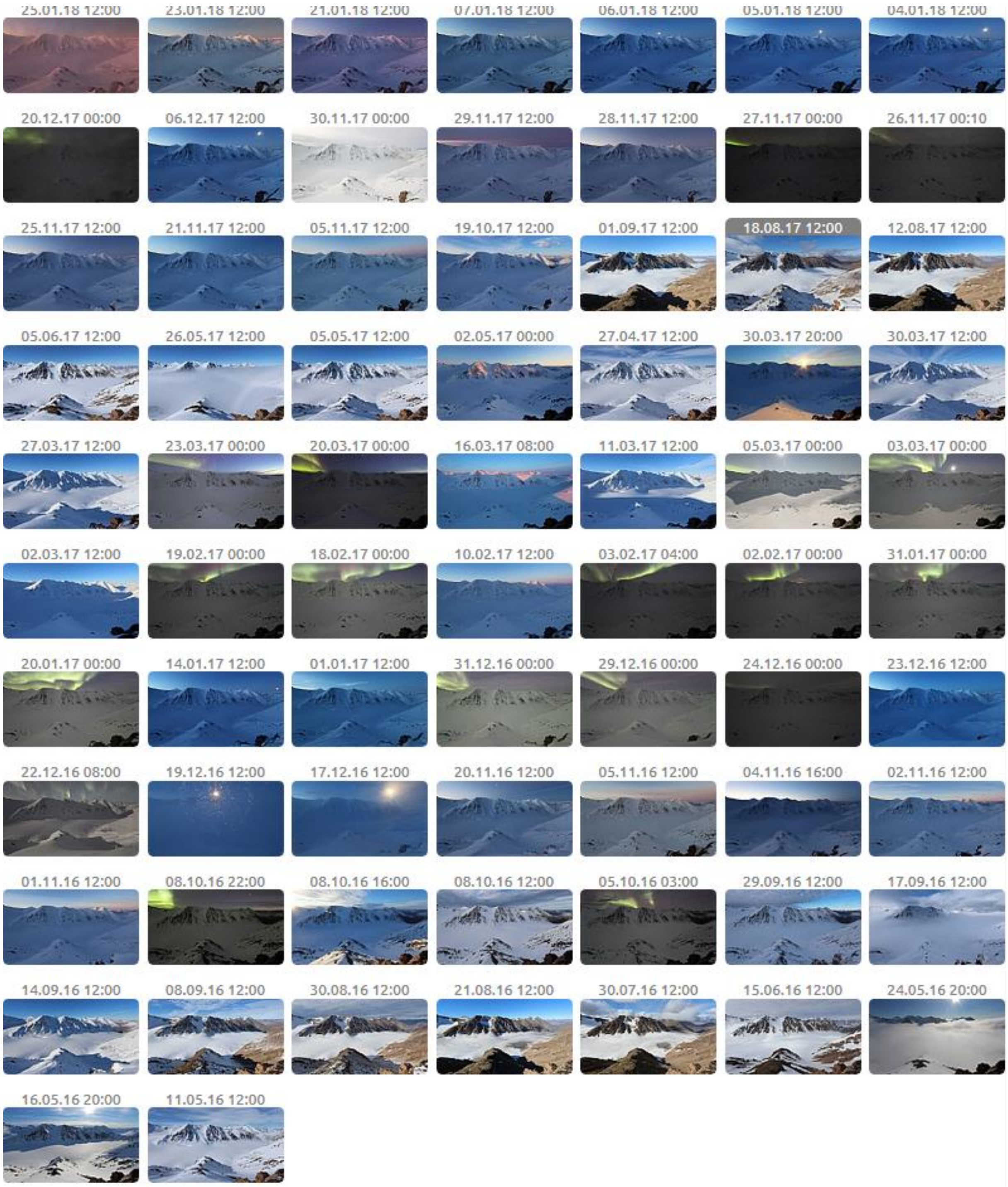


Figure: Correlation 1) of 6 years of annual and winter mass balances. 2) of 9 years of annual mass balance and accumulation area ratio (AAR), 3) of 9 years of annual mass balance and equilibrium line altitude (ELA).

Acknowledgements

The authors thank Anders Anker Bjørk from the Natural History Museum of Denmark for taking the fotographs of Freya Glacier in August 2016 and the Zackenberg Research Station for providing logistic support during field work. We thank also Gerhard Keuschnig and Flori Radlherr from foto-webcam.eu for the good collaboration and especially their commitment and efforts to adapt the automatic camera system to Arctic conditions and for data transfer via Iridium-Satellite. Finally, we thank Kirstine Skov for fieldwork assistance.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11.05.16 12:00

Appendix: AWS Maintainence/Establishment Details (7.5.2016)

AWS maintenance / establishment checklist

Station name	FREYA
People present	BERNHARDT, MICHELE (Instructed by:)
Purpose of visit	ESTABLISHMENT
Date & time	Arrival: 7.5.2016 1300 Departure: 1900
Transport	By: SNOW SCOOTER From: ZERO
Weather	SUN, LITTLE WIND

Remarks on state of AWS / maintenance / establishment

AWESOME

(but ablation hose and thermistor string will be installed next year due to lack of enough Kovaks auger flights on sledge)

Figure: Calibration constants of the net radiometer: (SWU/SWL/LWU/LWL//10.59/10.82/11.52/9.57)

Part	Old part number	New part number, if replaced	Potential maintenance tasks
Radiometer			- Aligned with mast: Y/N - Clean: Y/N
Inclinometer		905	- Aligned with radiometer within 0.5°: Y/N
Satellite antenna		36	
Wind sensor		[illegible]	
Temperature / humidity assembly			- New HygroClip with old assembly: Y/N - Fan spins and sounds OK: Y/N
Or: HygroClip		HC2-S3 61318908	- Large offset in HygroClip temperature: Y/N
Sonic ranger on AWS			- Old sensor with new membrane: Y/N - Clicking as it should: Y/N
Solar panel		C1090227 [illegible]	- Output OK: Y/N - Clean: Y/N
GPS antenna		[illegible]	- Stuck to top of logger enclosure: Y/N
Data logger		E9348	- New internal battery in old logger: Y/N - New operating system: Y/N - New logger program: Y/N
Card reader		10721	- LED either green of flashing orange (active): Y/N
Multiplexer		E10089	- Clicking as it should: Y/N
Iridium modem IMEI number		1852400	- Transmissions tested: Y/N - Problems: Y/N
Barometer		5879376	
Sonic ranger on stakes		6329	- Old sensor with new membrane: Y/N - Clicking as it should: Y/N
Thermistor string		/	- New string in use, but old one still in ice: Y/N
Ablation hose assembly		/	- New hose in use, but old one still in ice: Y/N - Air in current hose: Y/N - Air removed from current hose: Y/N - Added 50% antifreeze mix to bladder: Y/N
Logger enclosure	- Replaced (including everything inside): Y/N - New vent filter in logger enclosure: Y/N - Moisture inside: Y/N - New desiccant bags (2): Y/N		
Battery box	- New box with new batteries: Y/N - Old box with new batteries: Y/N - Moisture inside: Y/N - New desiccant bags (2): Y/N		
Stakes	- New ones drilled in: Y/N - Length: 2 / 4 / 6 / 8 / 10 m		
Tripod	- New parts: Y/N		

Metadata after maintenance / establishment

Time difference between logger clock and UTC	Ø	+ / -
Adjust logger time to UTC (be sure PC runs on UTC time)		Y / N
Download data to PC and/or change CF Card (wait for green light)	/	Y / N
Name of logger program	FREYA 2015	
Photo or screen dump of values in fast scan mode		Y / N
Latitude (dd mm.mmm)	SEE GPS STAKE	
Longitude (dd mm.mmm)		
Altitude (m)		
Photos of tripod, sensors, logger box wiring etc. (more is better)		Y / N
Mast tilt in boom direction (+ if radiometer tilting down)	-4	°
Mast tilt across boom looking from radiometer (- if clockwise)	+5	°
Boom direction relative to north (radiometer should point to true south)	204	° true/magn
Wind sensor box direction along boom? If not, change.		Y / N
Radiometer aligned with mast and inclinometer? If not, align.		Y / N
Temperature / humidity height (bottom of casing – surface)	335	cm
Sonic ranger on AWS height (membrane – surface)	340	cm
Wind sensor height (center of propeller – surface)	385	cm
Sonic ranger on stakes height (membrane – surface)	58	cm
Free length of stake – outer, holding boom with sonic ranger	86	cm
Free length of stake – middle	76	cm
Free length of stake – outer, holding boom without sonic ranger	80	cm
Free length of ablation hose on/above the ice surface	/	cm
Alt: depth of ablation hose using markings on hose	/	cm
Height of ablation hose fluid level above the ice surface	/	cm
Vertical difference in surface height (at station – at hose) (approx)	/	cm
Length of thermistor string on surface from surface marking	/	cm
Height of surface irregularities	3	cm