Supplement to:

Changes of the tropical glaciers throughout Peru between 2000 and 2016 – Mass balance and area fluctuations

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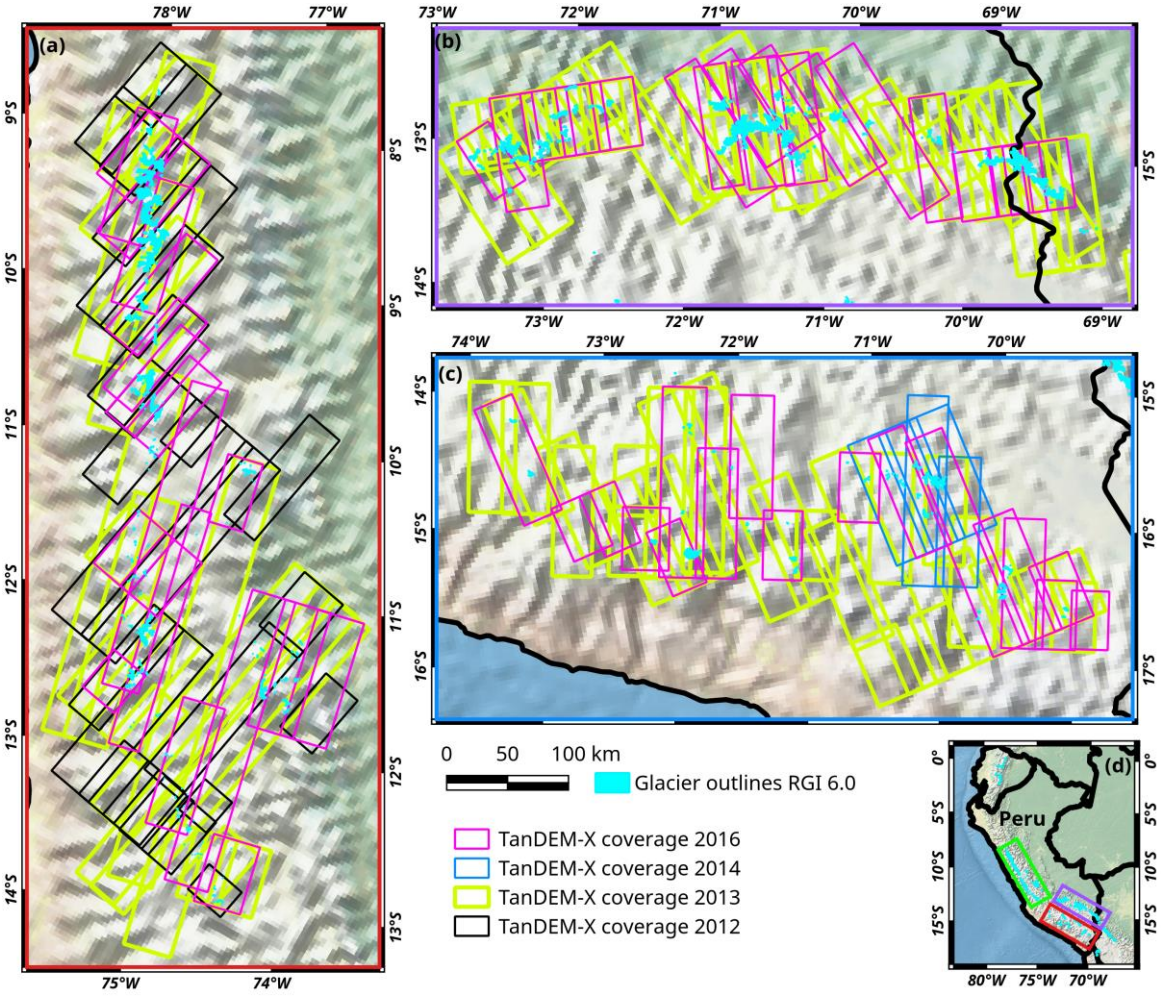

Figure S1. Coverage of the studied areas by TanDEM-X data. Panels (a-c): glacier subregions in Peru according to Sagredo and Lowell (2012); (a) subregion R1: northern wet outer tropics; (b) subregion R2: southern wet outer tropics; (c) subregion R3: dry outer tropics. Panel (d): overview map of Peru. Coloured rectangles indicate the locations of the subregions (same frame colours). Light blue areas: glacier coverage based on RGI 6.0.

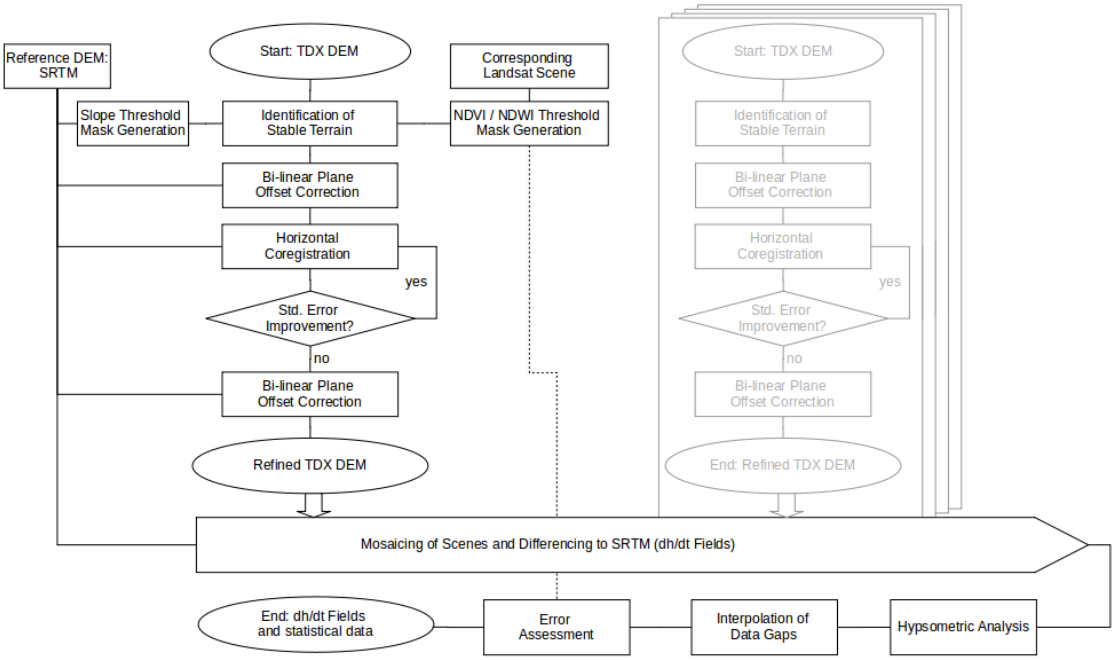

Figure S2. Flow chart of processing chain to perform coregistration, mosaicking, gap filling and error evaluation of TanDEM-X DEMs

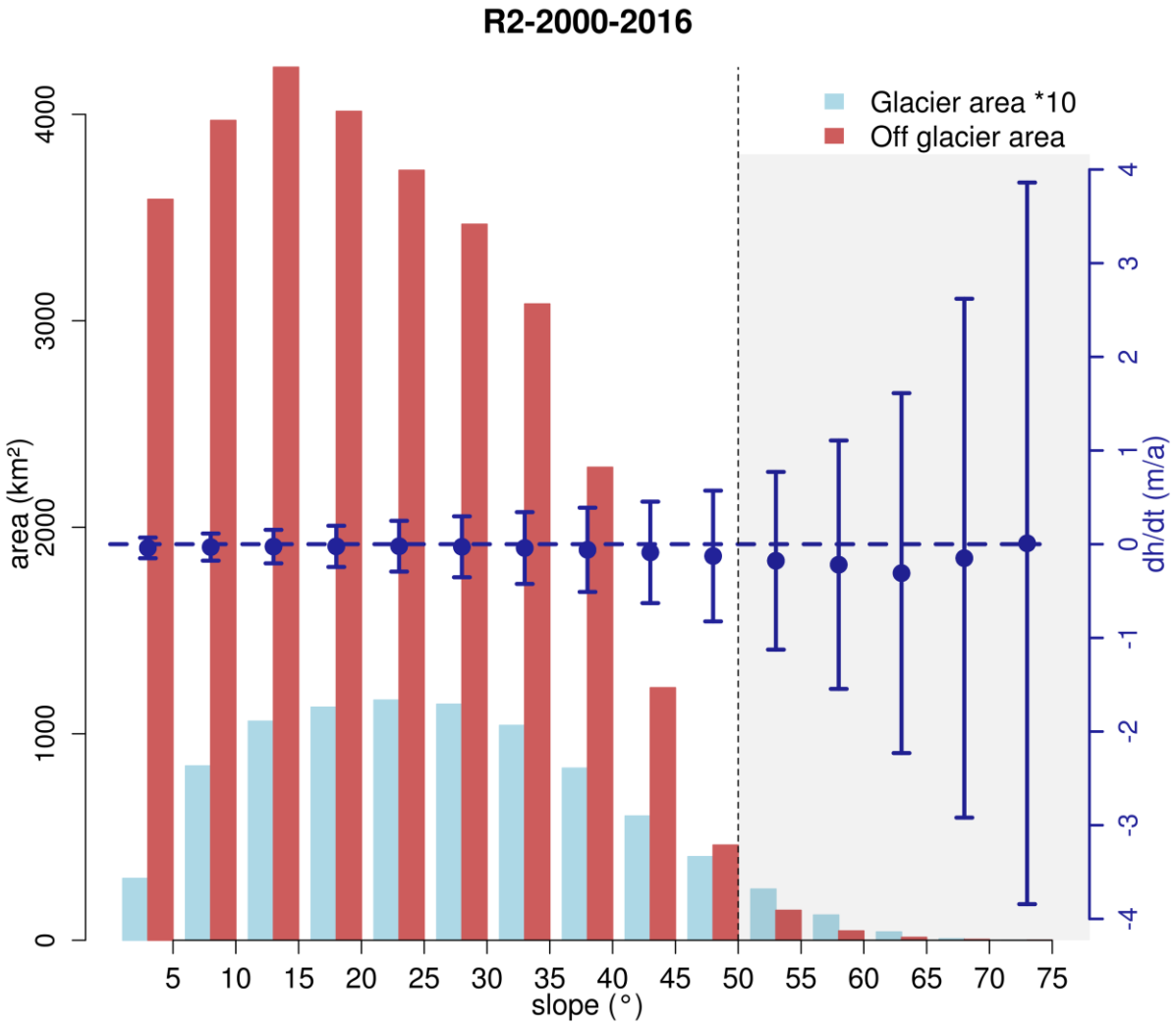

Figure S3. Off-(red) and on-glacier (light blue) area and off-glacier elevation change (blue dots) distributions in dependency on slope in subregion R2 for the period 2000-2016. Error bars represent NMAD of Δh/Δt values in the individual slope interval. Dotted line indicates the applied slope threshold (see Section 4.2). Glacier area measurements are based on the glacier outlines from 2000. Note: For better representation, on-glacier areas are scaled by a factor of 10.

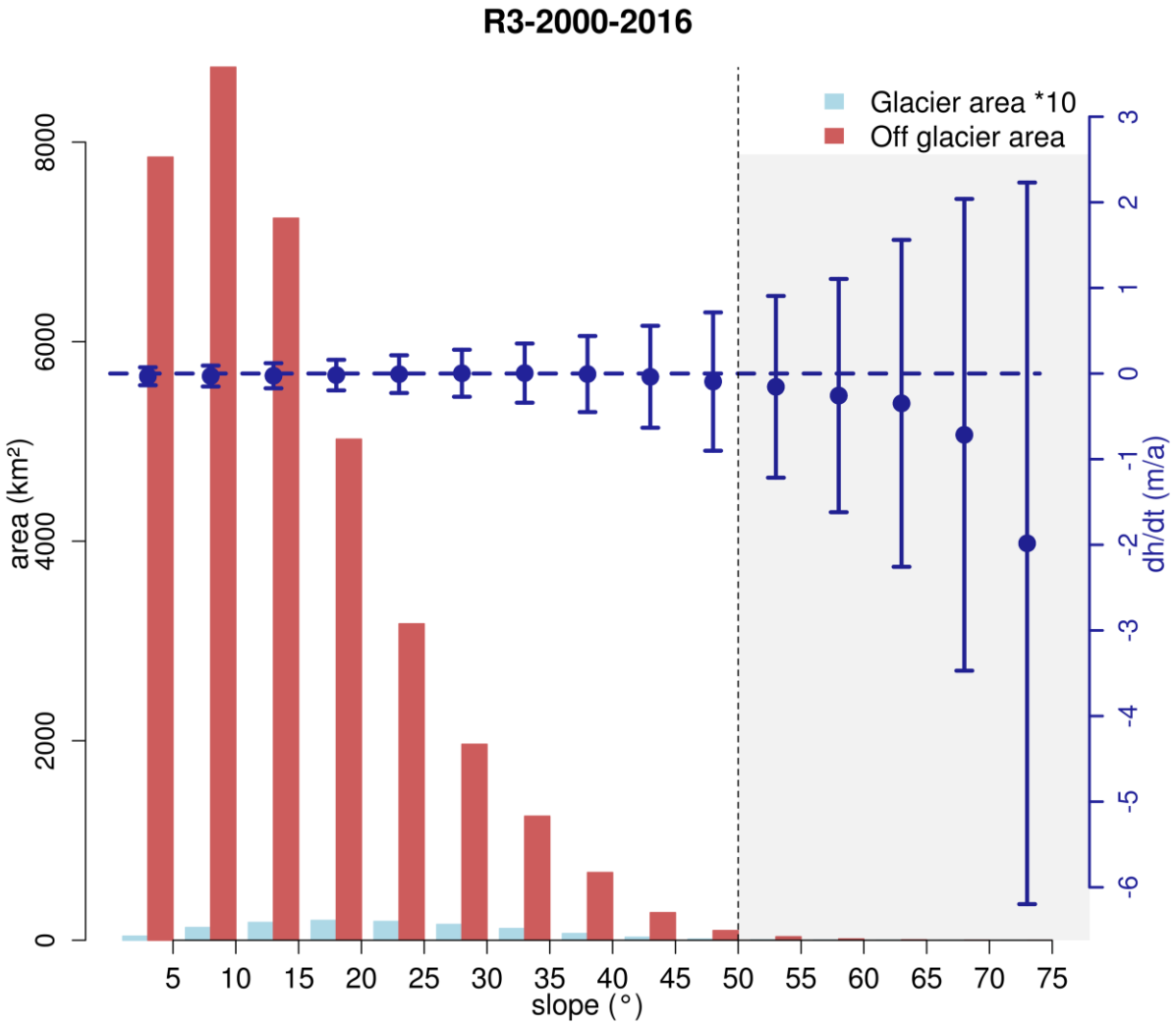

Figure S4. Off-(red) and on-glacier (light blue) area and off-glacier elevation change (blue dots) distributions in dependency on slope in subregion R3 for the period 2000-2016. Error bars represent NMAD of Δh/Δt values in the individual slope interval. Dotted line indicates the applied slope threshold (see Section 4.2). Glacier area measurements are based on the glacier outlines from 2000. Note: For better representation, on-glacier areas are scaled by a factor of 10.

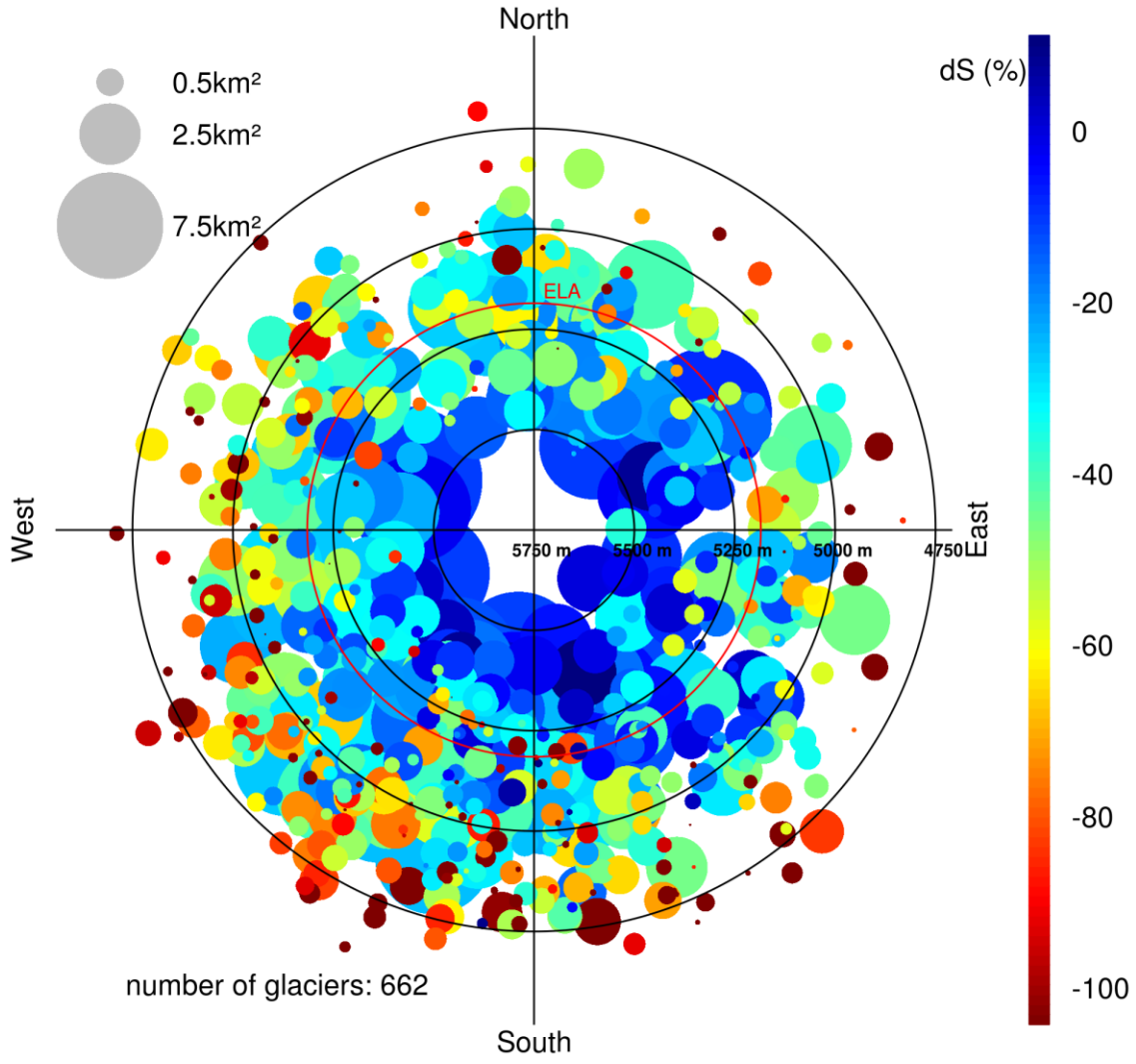

Figure S5. Polar plot of relative area changes (dot colour) in subregion R2 in the period 2000-2016 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

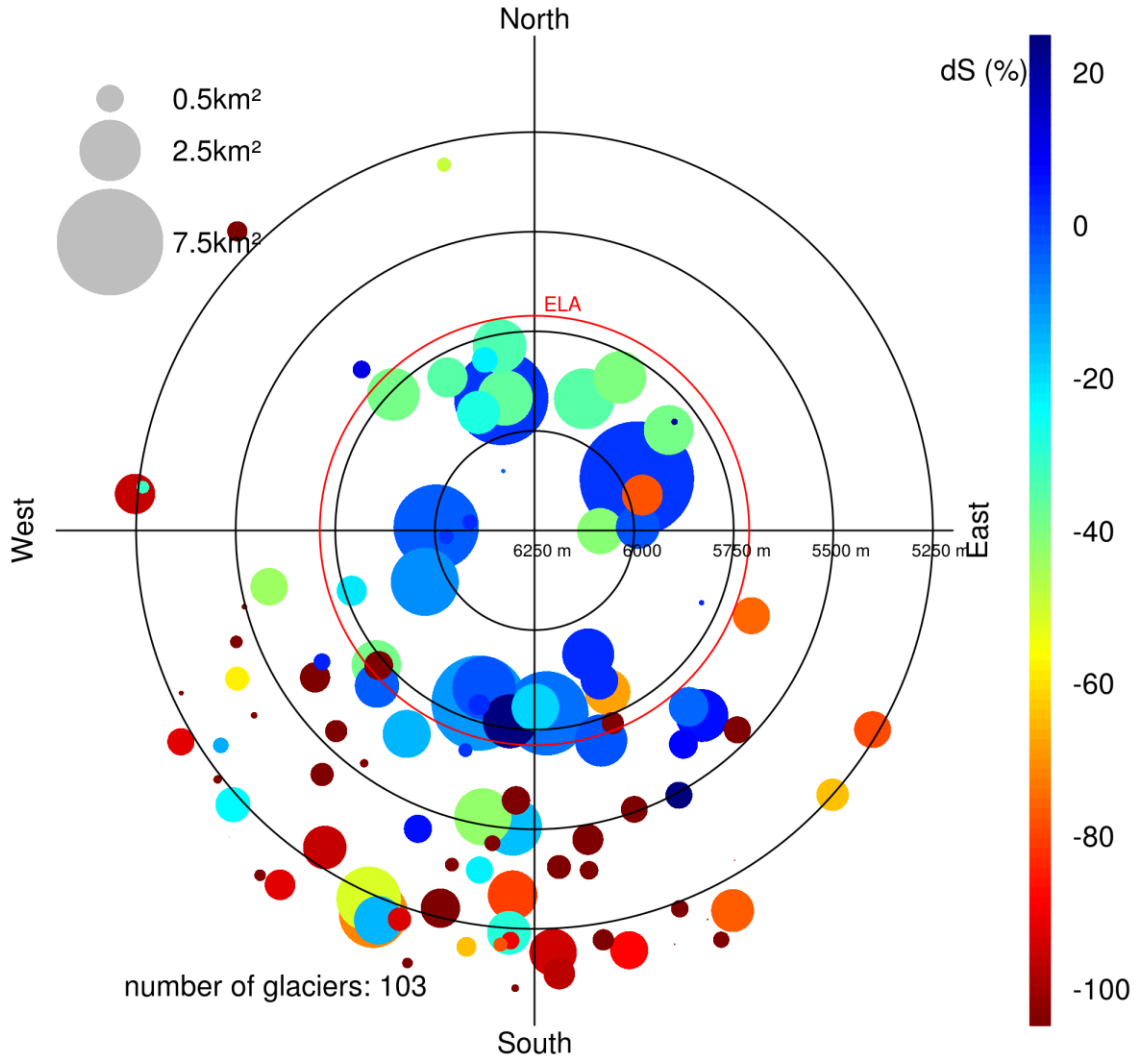

Figure S6. Polar plot of relative area changes (dot colour) in subregion R3 in the period 2000-2016 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

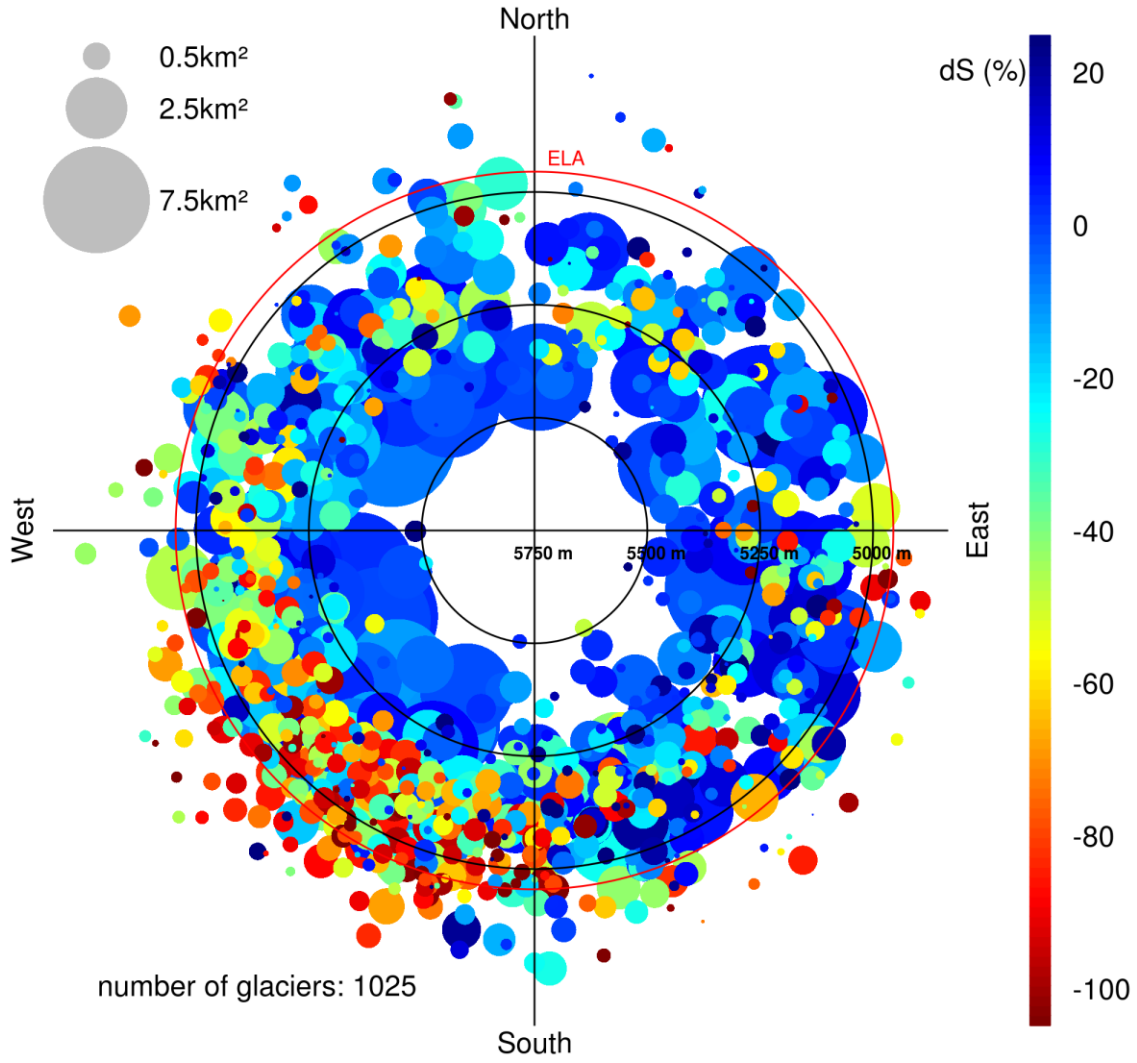

Figure S7. Polar plot of relative area changes (dot colour) in subregion R1 in the period 2000-2013 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

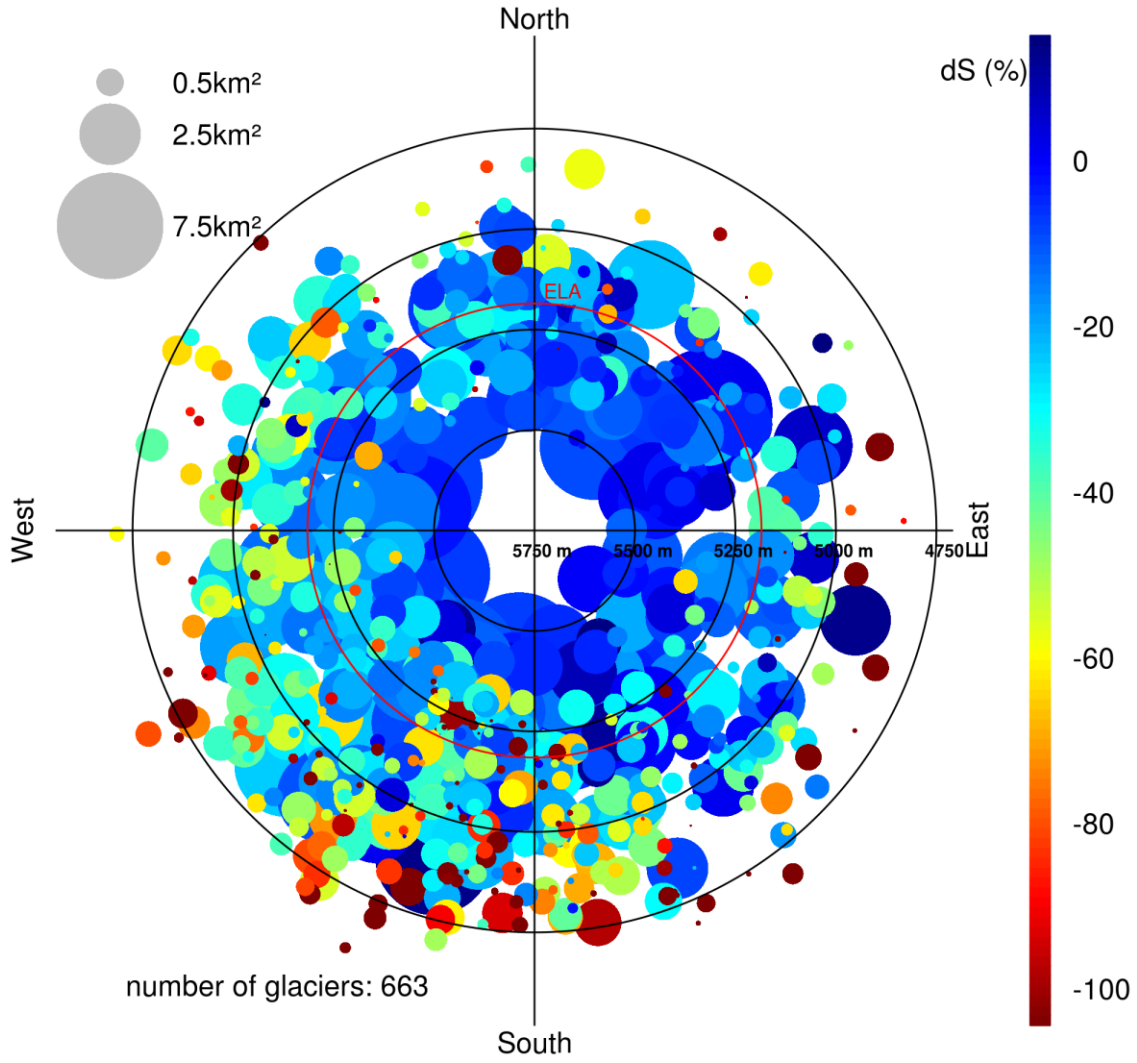

Figure S8. Polar plot of relative area changes (dot colour) in subregion R2 in the period 2000-2013 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

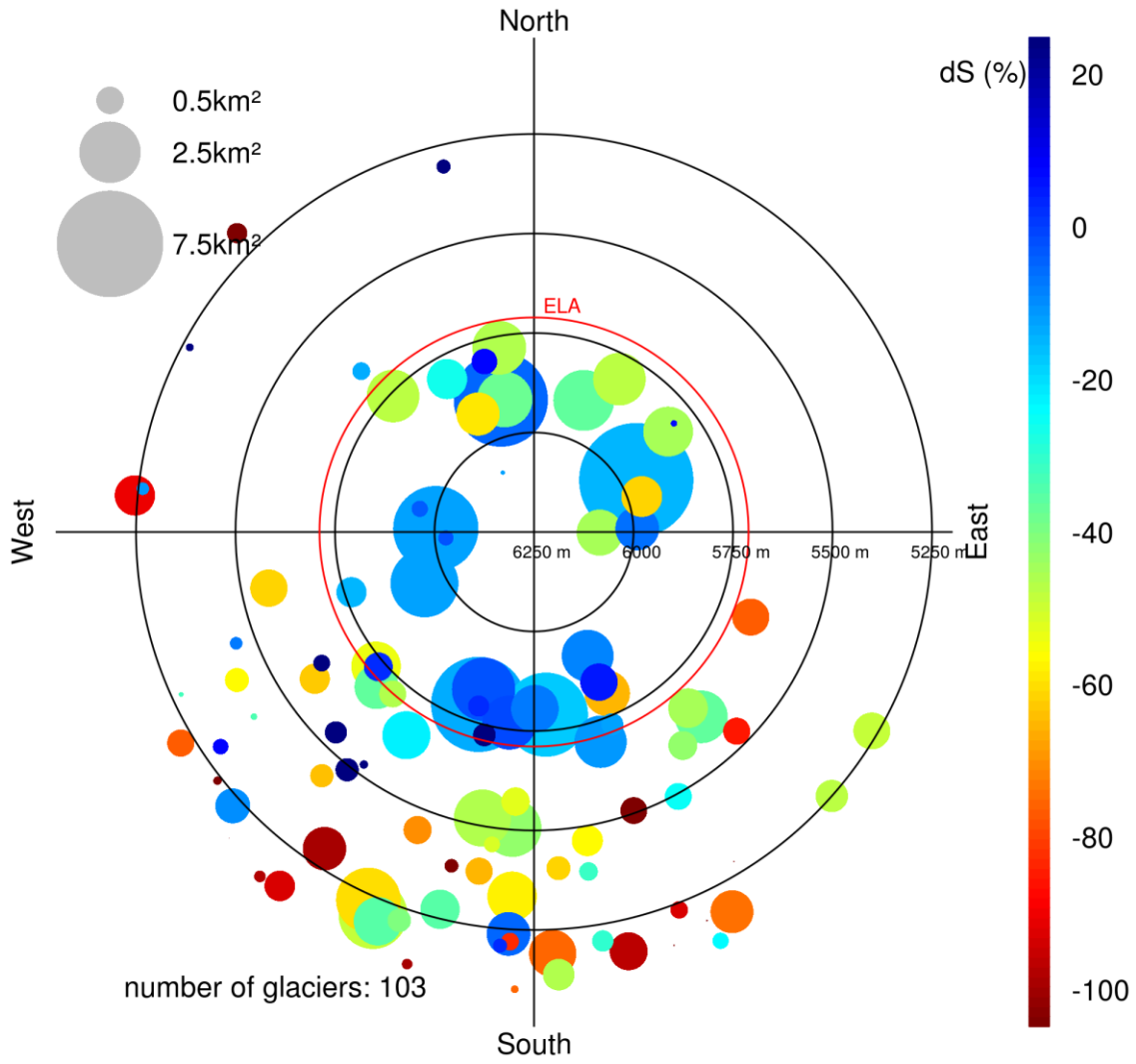

Figure S9. Polar plot of relative area changes (dot colour) in subregion R3 in the period 2000-2013 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

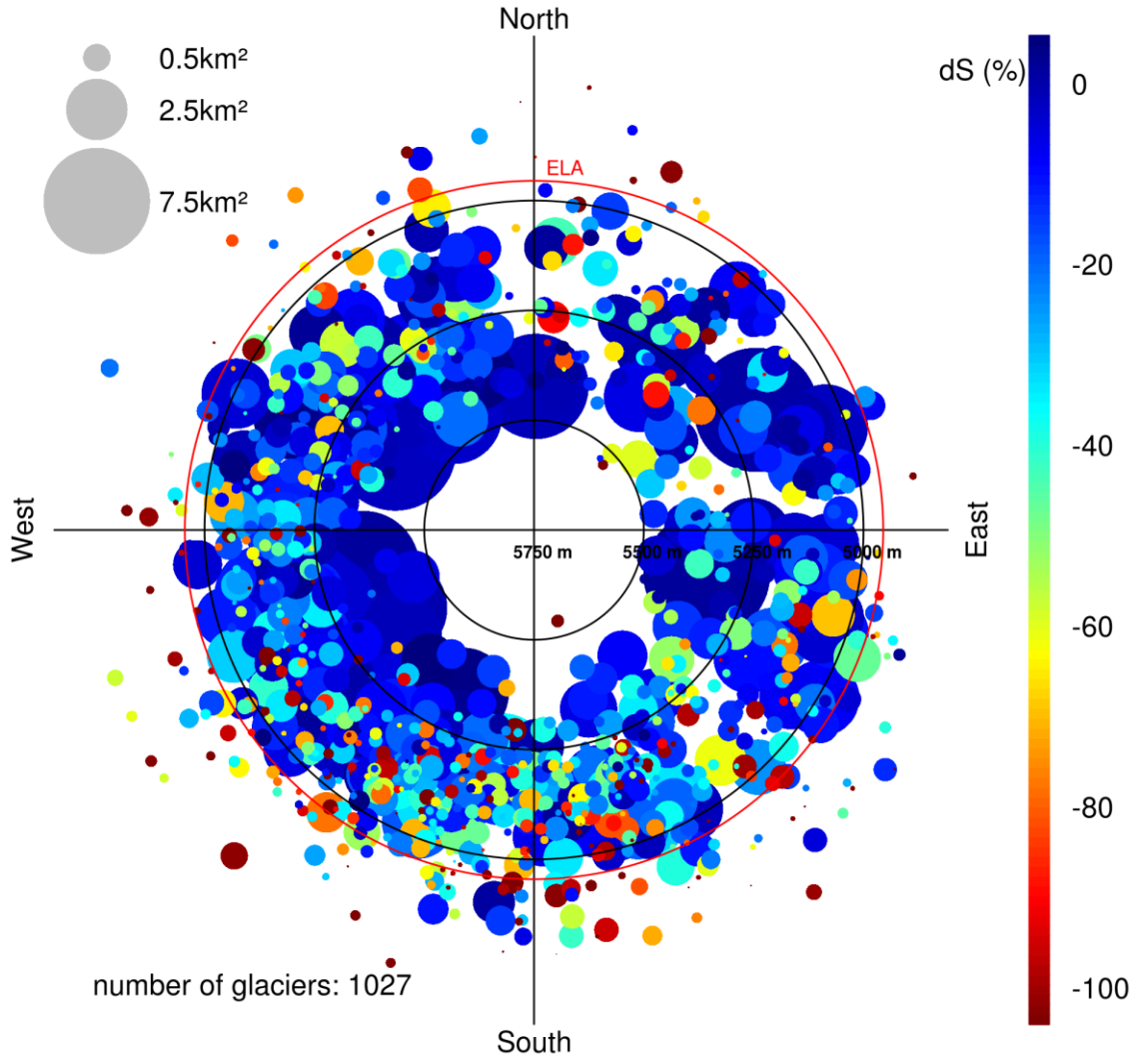

Figure S10. Polar plot of relative area changes (dot colour) in subregion R1 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

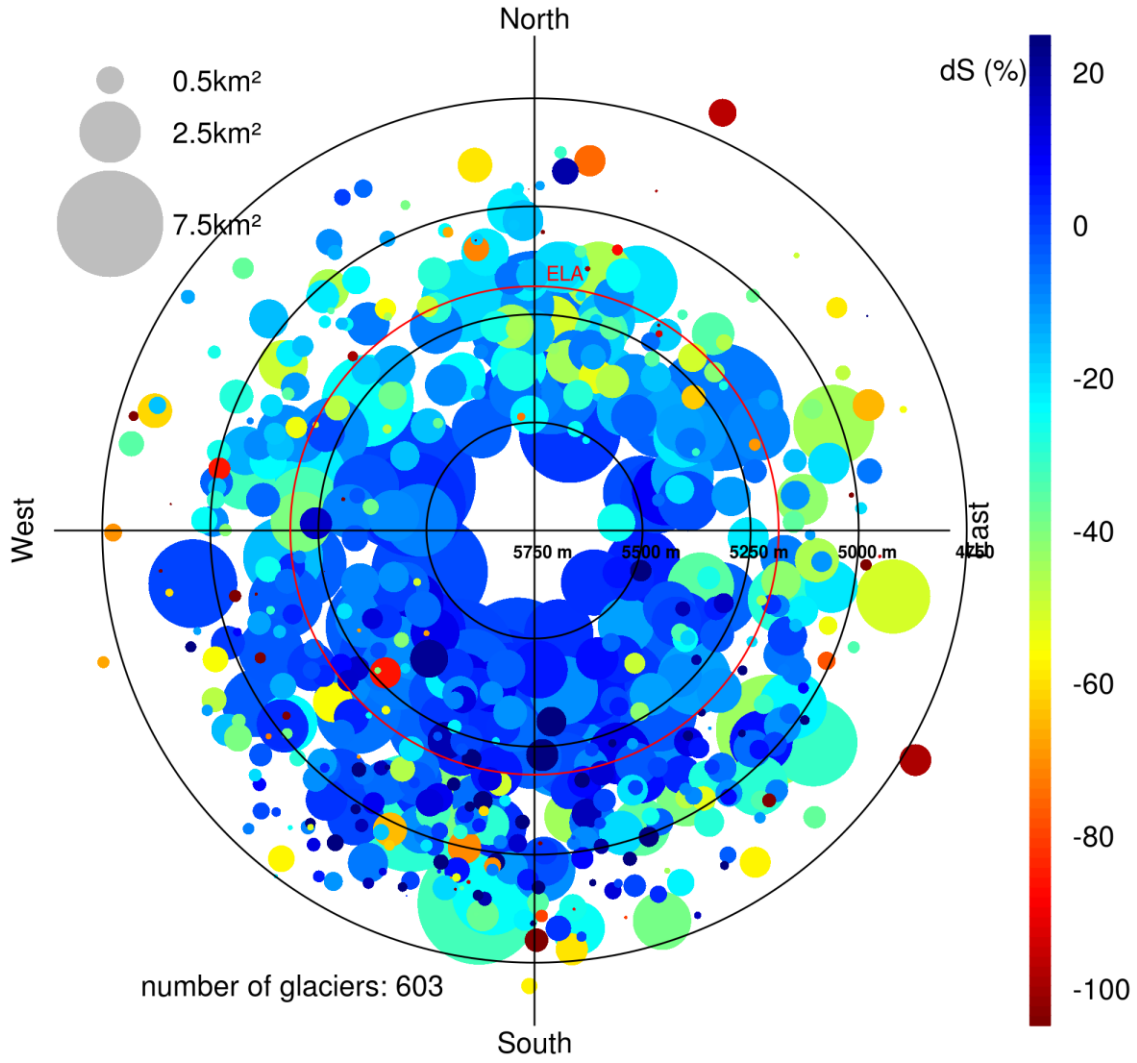

Figure S11. Polar plot of relative area changes (dot colour) in subregion R2 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

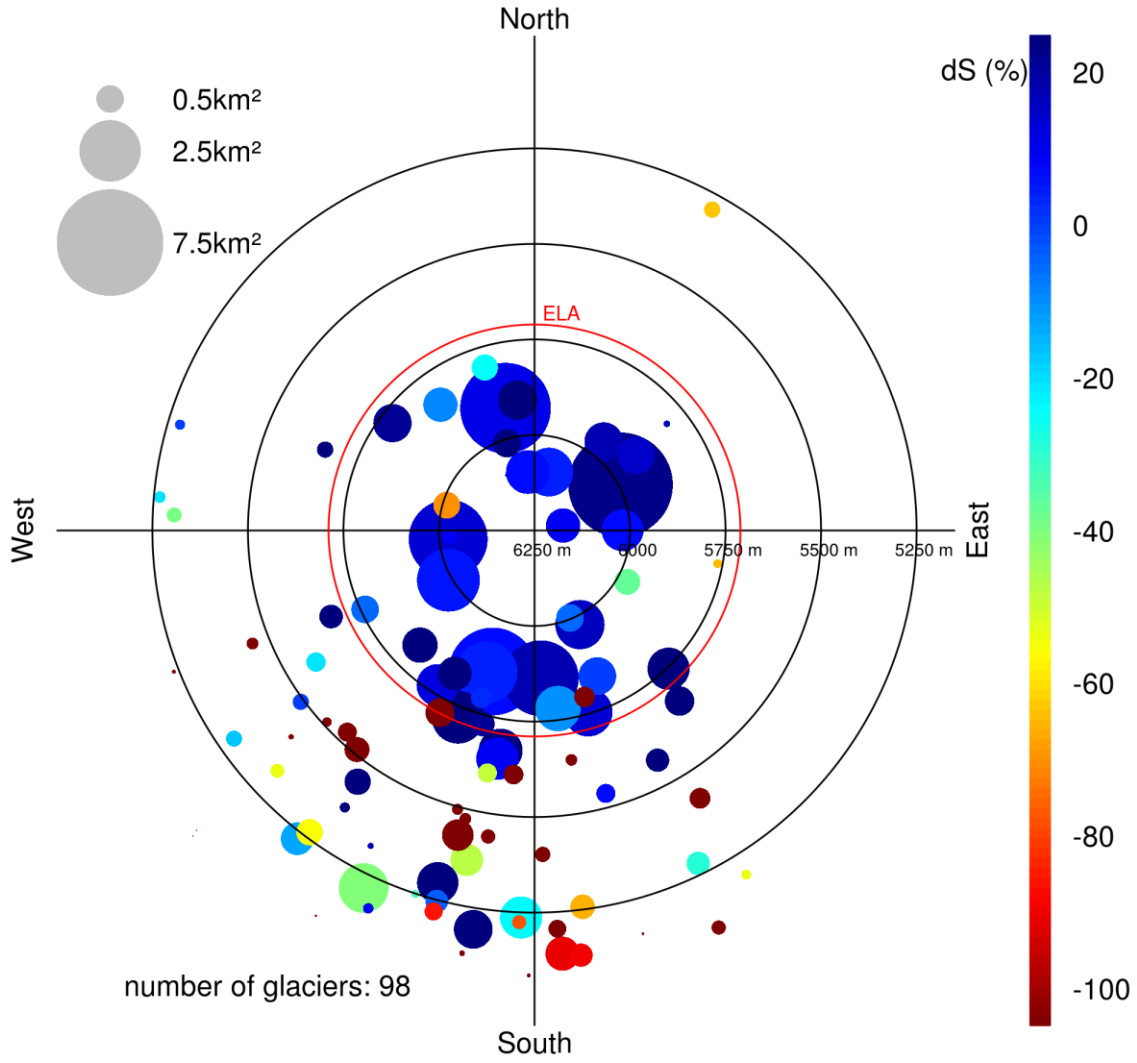

Figure S12. Polar plot of relative area changes (dot colour) in subregion R3 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3.

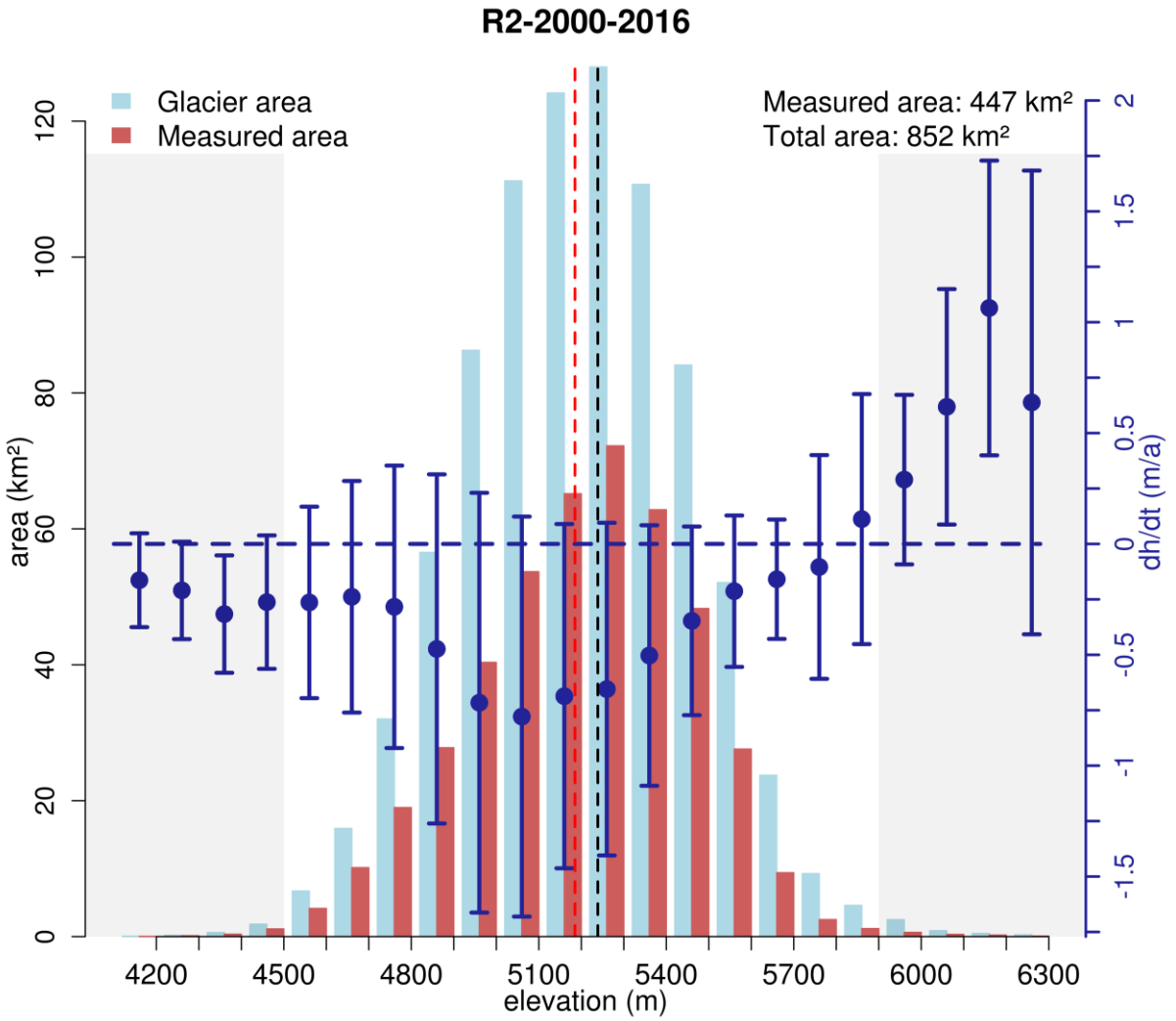

Figure S13. Hypsometric distribution of glacier area with elevation change (Δh/Δt) measurements (red) and total glacier area (light blue) in subregion R2 in the interval 2000-2016. Blue dots represent the mean Δh/Δt value in each elevation interval. Error bars indicate NMAD of Δh/Δt for each hypsometric bin. Grey areas mark the lower and upper 1% quantile of the glacier area distribution. Black dashed line: mean glacier elevation; Red dashed line: equilibrium line altitude (ELA), see also Table S3. Area measurements are based on the glacier outlines from 2000, considering only regions with slopes below applied slope threshold (50°, see Section 4.2)

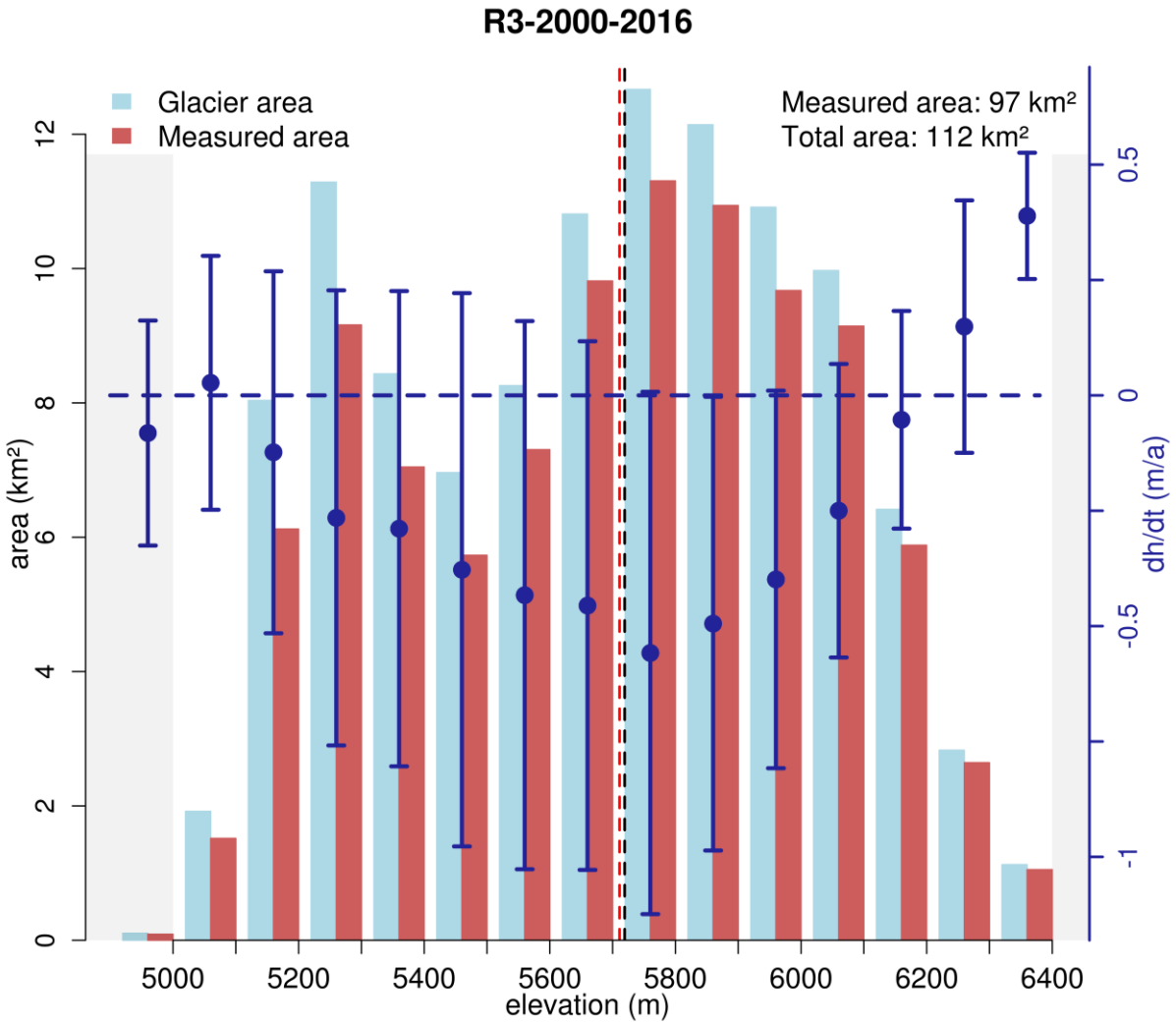

Figure S14. Hypsometric distribution of glacier area with elevation change (Δh/Δt) measurements (red) and total glacier area (light blue) in subregion R3 in the interval 2000-2016. Blue dots represent the mean Δh/Δt value in each elevation interval. Error bars indicate NMAD of Δh/Δt for each hypsometric bin. Grey areas mark the lower and upper 1% quantile of the glacier area distribution. Black dashed line: mean glacier elevation; Red dashed line: equilibrium line altitude (ELA), see also Table S3. Area measurements are based on the glacier outlines from 2000, considering only regions with slopes below applied slope threshold (50°, see Section 4.2)

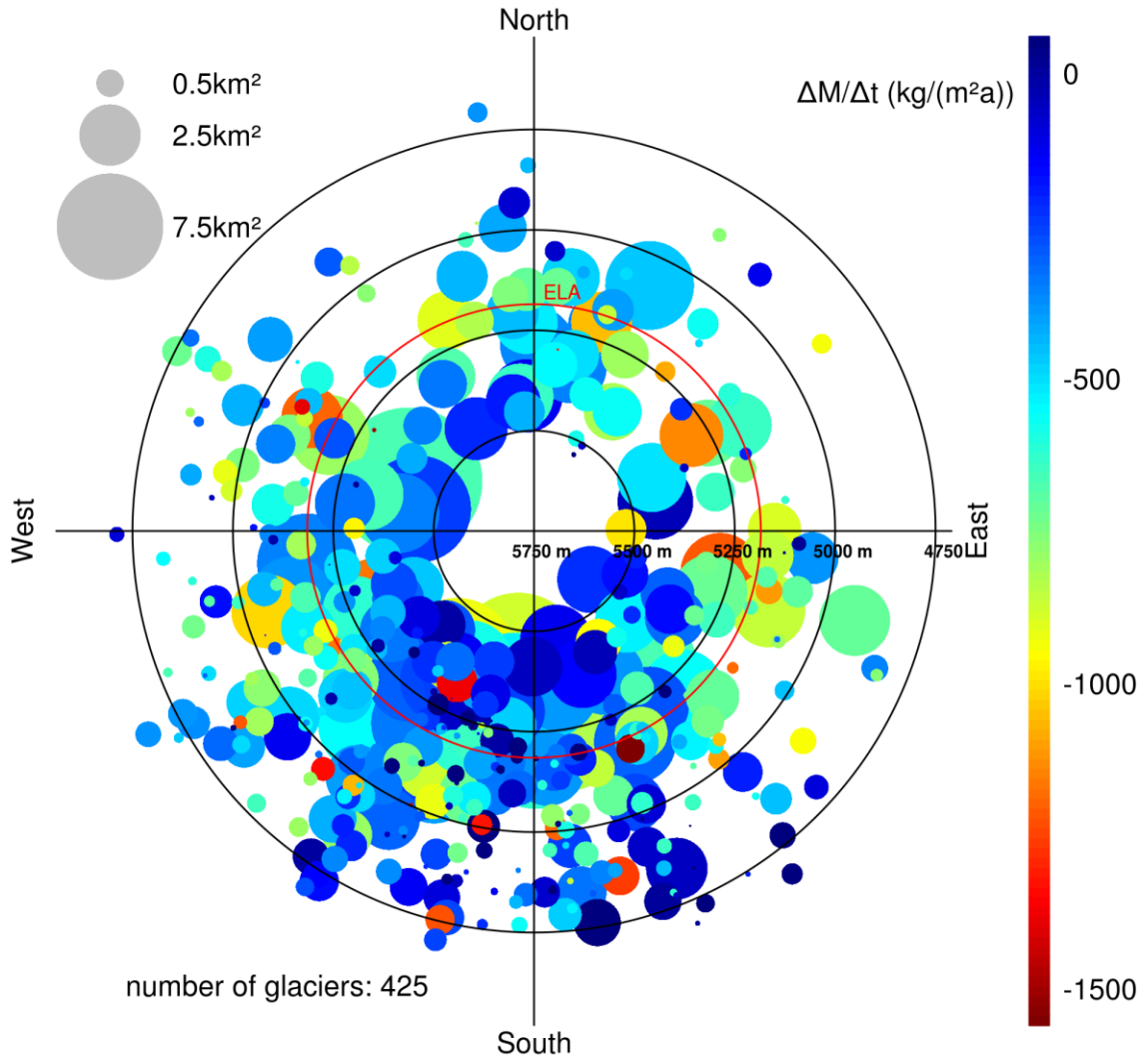

Figure S15. Polar plot of specific mass balance (dot colour) of individual glaciers in subregion R2 in the period 2000-2016 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3. Note: only glaciers with elevation change information >50% are included.

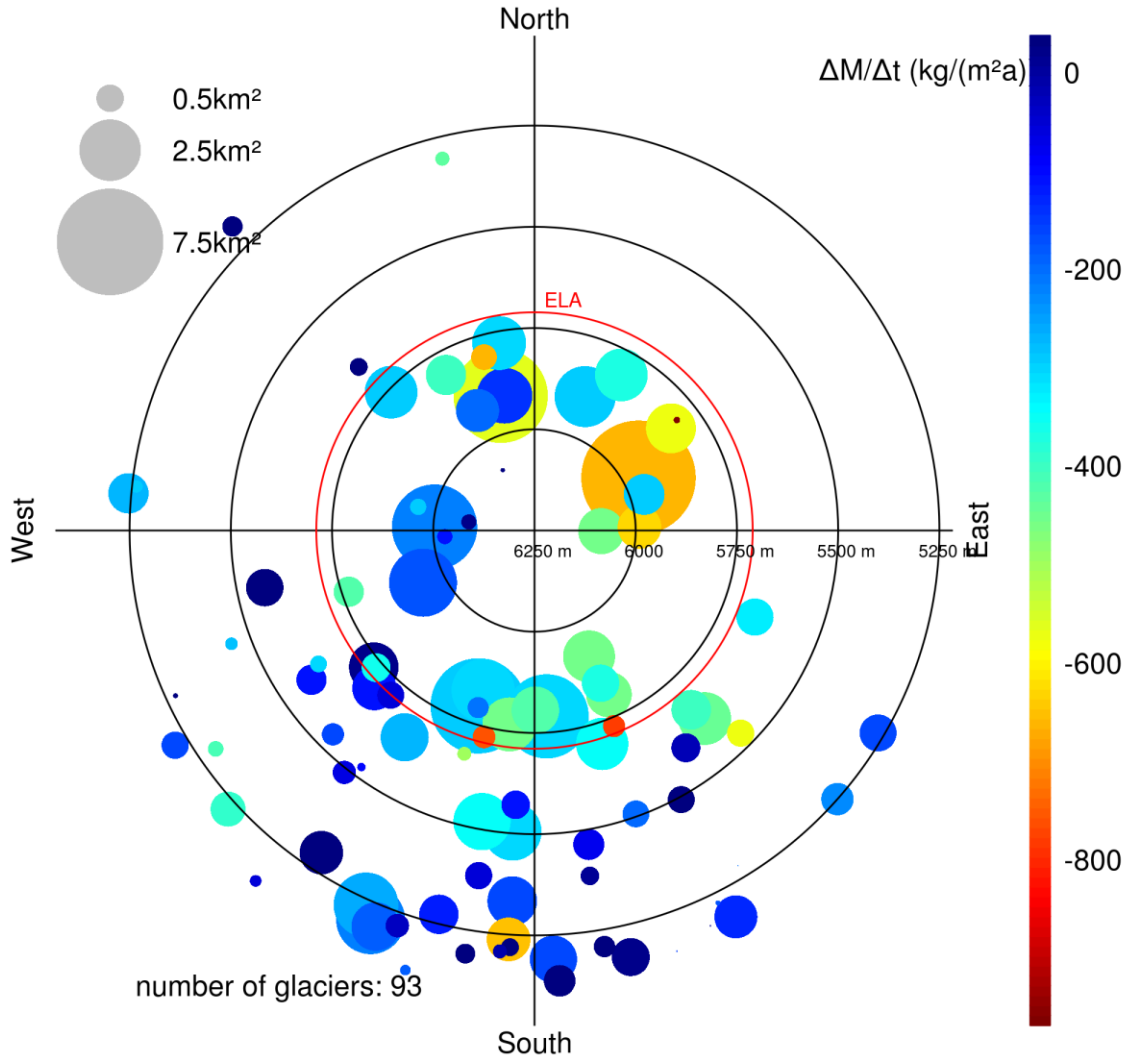

Figure S16. Polar plot of specific mass balance (dot colour) of individual glaciers in subregion R3 in the period 2000-2016 of individual glaciers. Dot size: glacier size in 2000; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3. Note: only glaciers with elevation change information >50% are included.

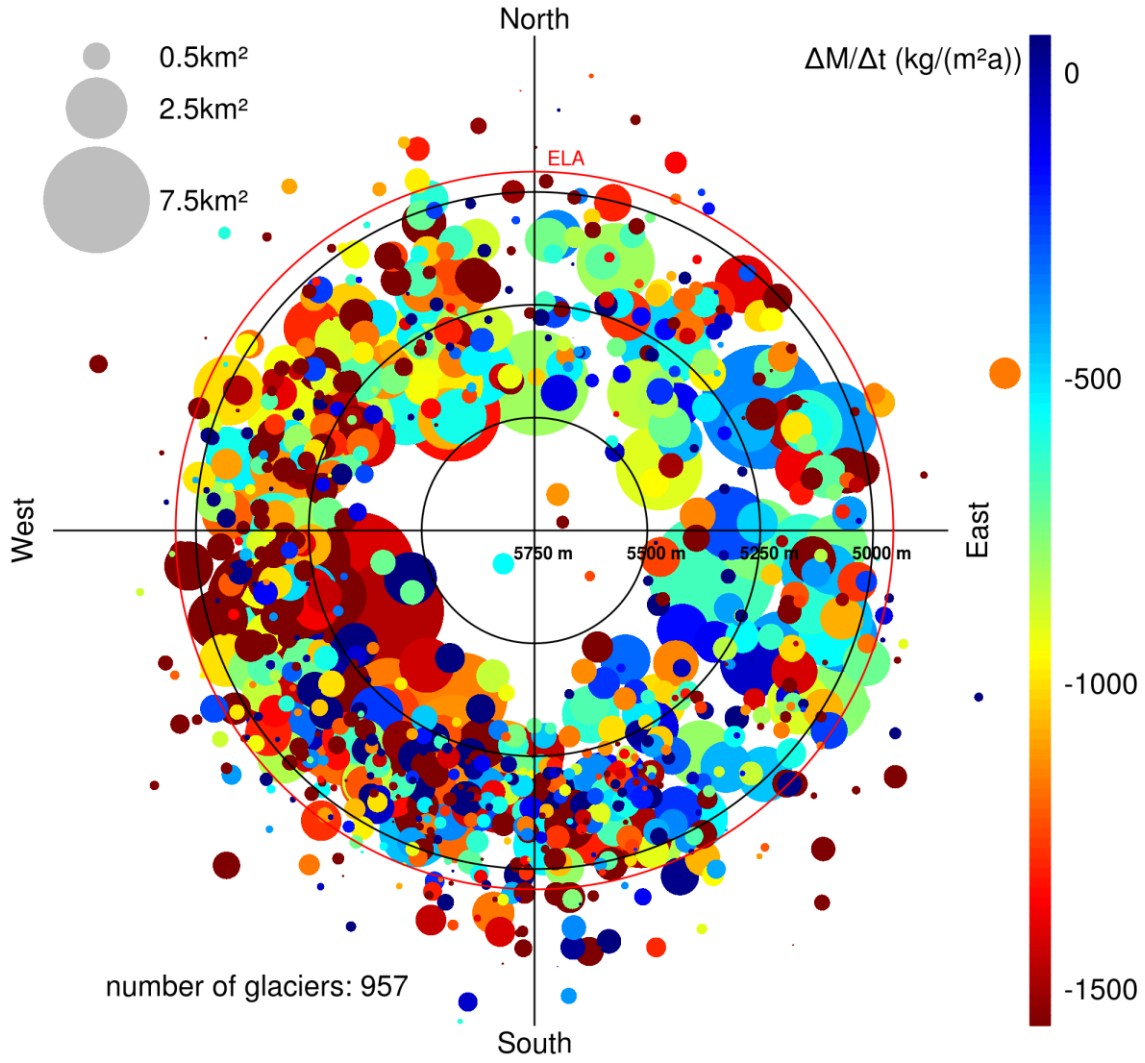

Figure S17. Polar plot of specific mass balance (dot colour) of individual glaciers in subregion R1 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3. Note: only glaciers with elevation change information >50% are included.

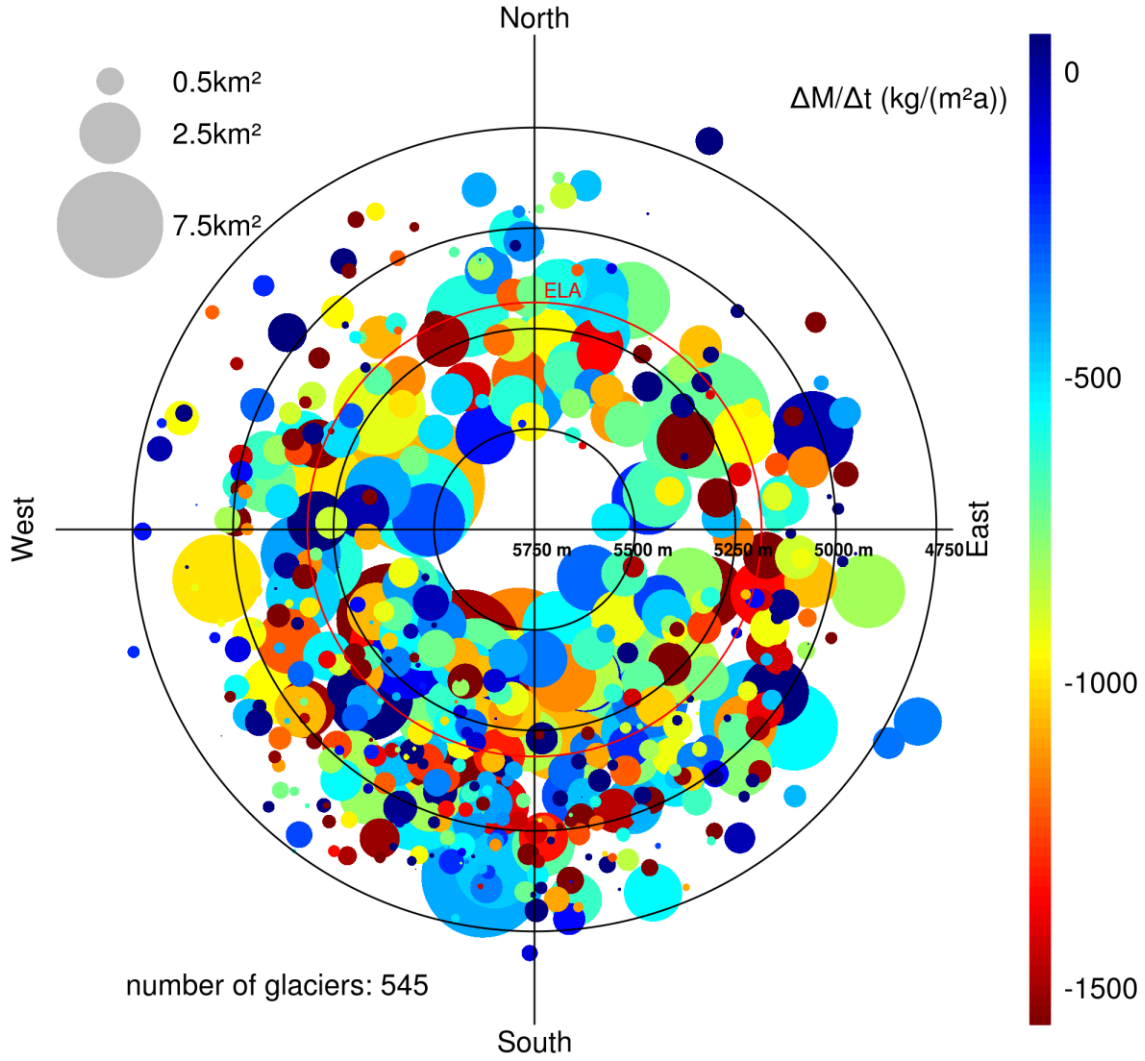

Figure S18. Polar plot of specific mass balance (dot colour) of individual glaciers in subregion R2 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3. Note: only glaciers with elevation change information >50% are included.

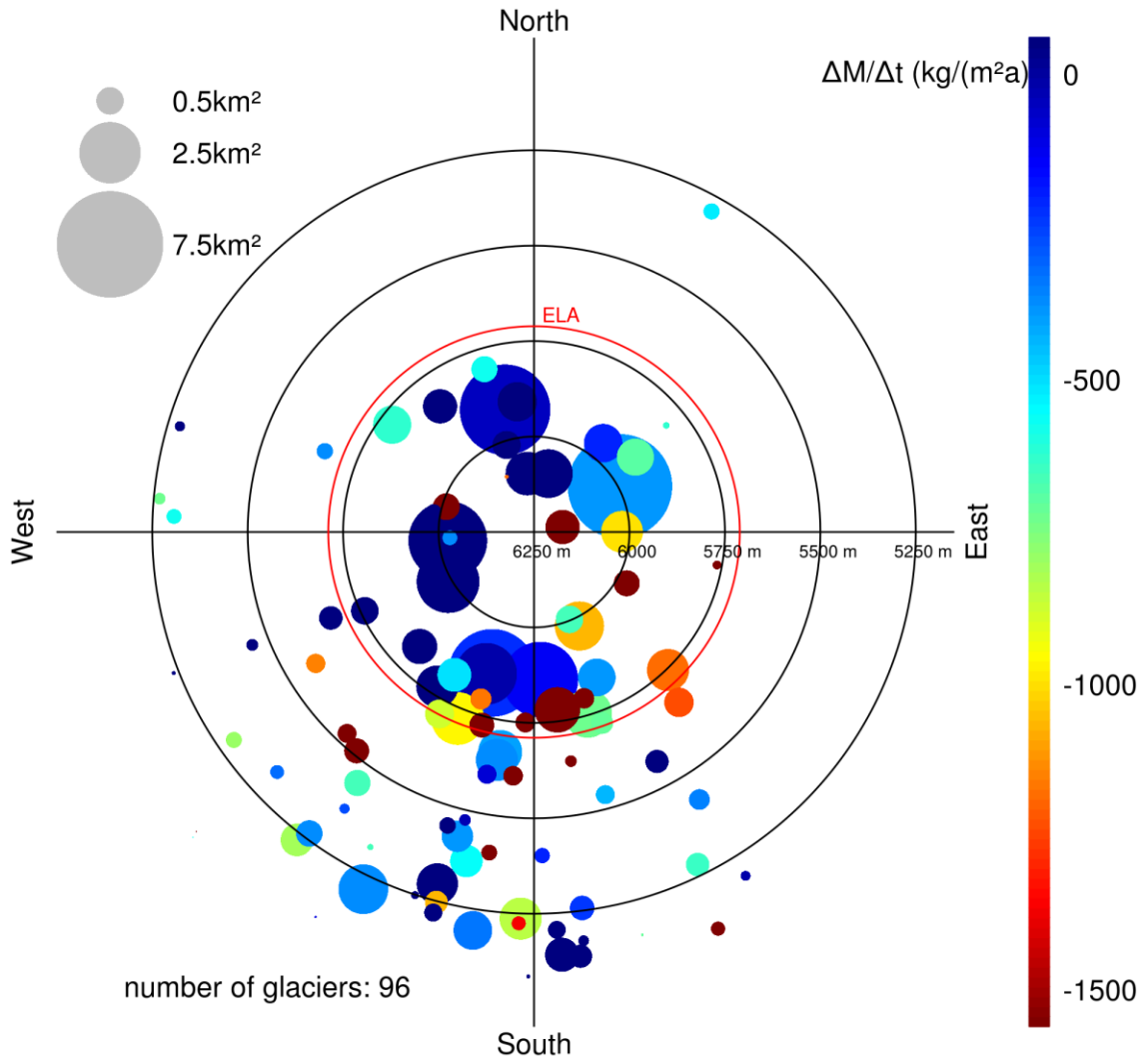

Figure S19. Polar plot of specific mass balance (dot colour) of individual glaciers in subregion R3 in the period 2013-2016 of individual glaciers. Dot size: glacier size in 2013; Radius: median elevation; Orientation: mean aspect. Red circle: equilibrium line altitude (ELA), see also Table S3. Note: only glaciers with elevation change information >50% are included.

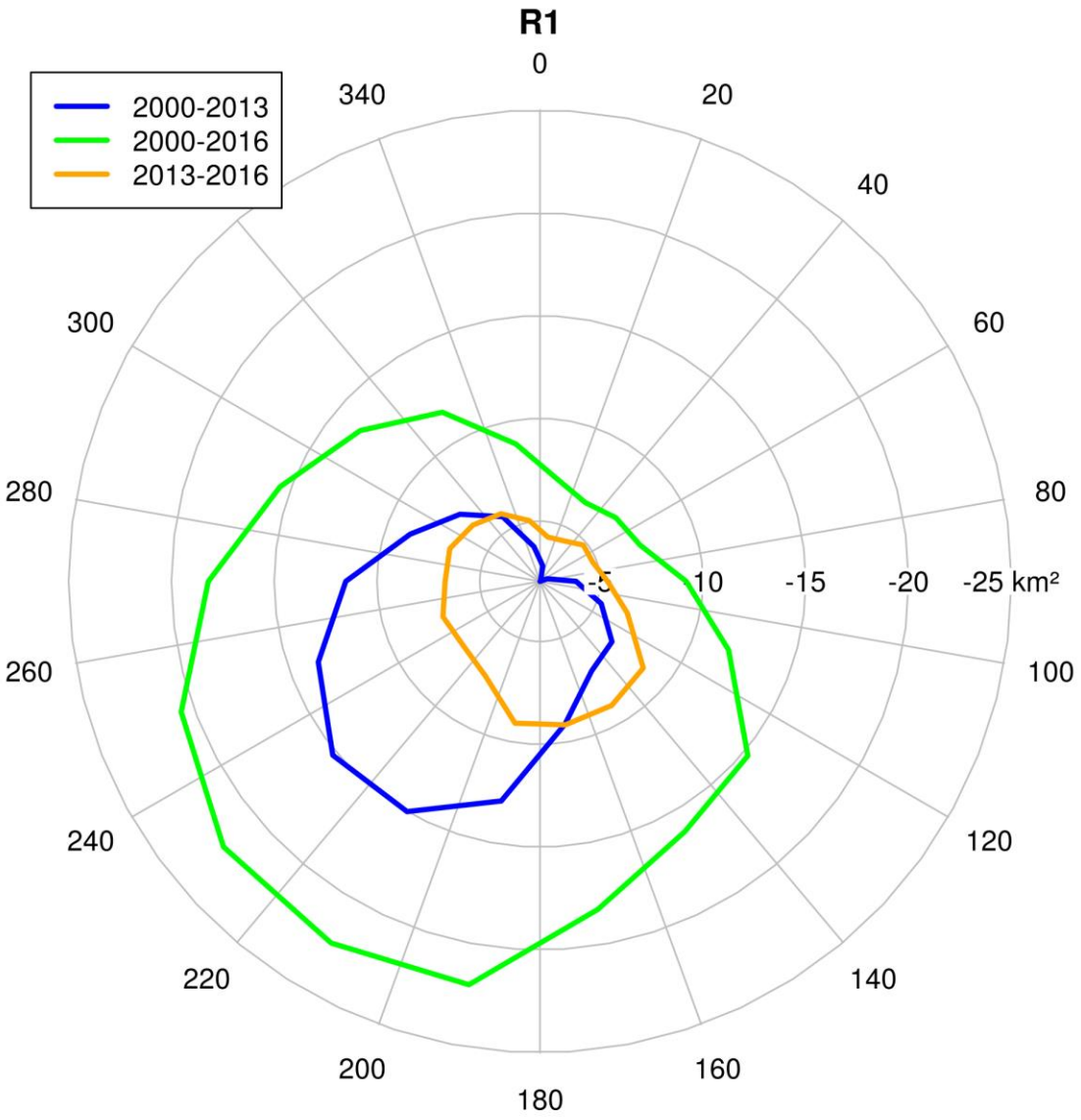

Figure S20. Polar plot of glacier area loss in subregion R1. The area losses are binned in aspect intervals of 20°.

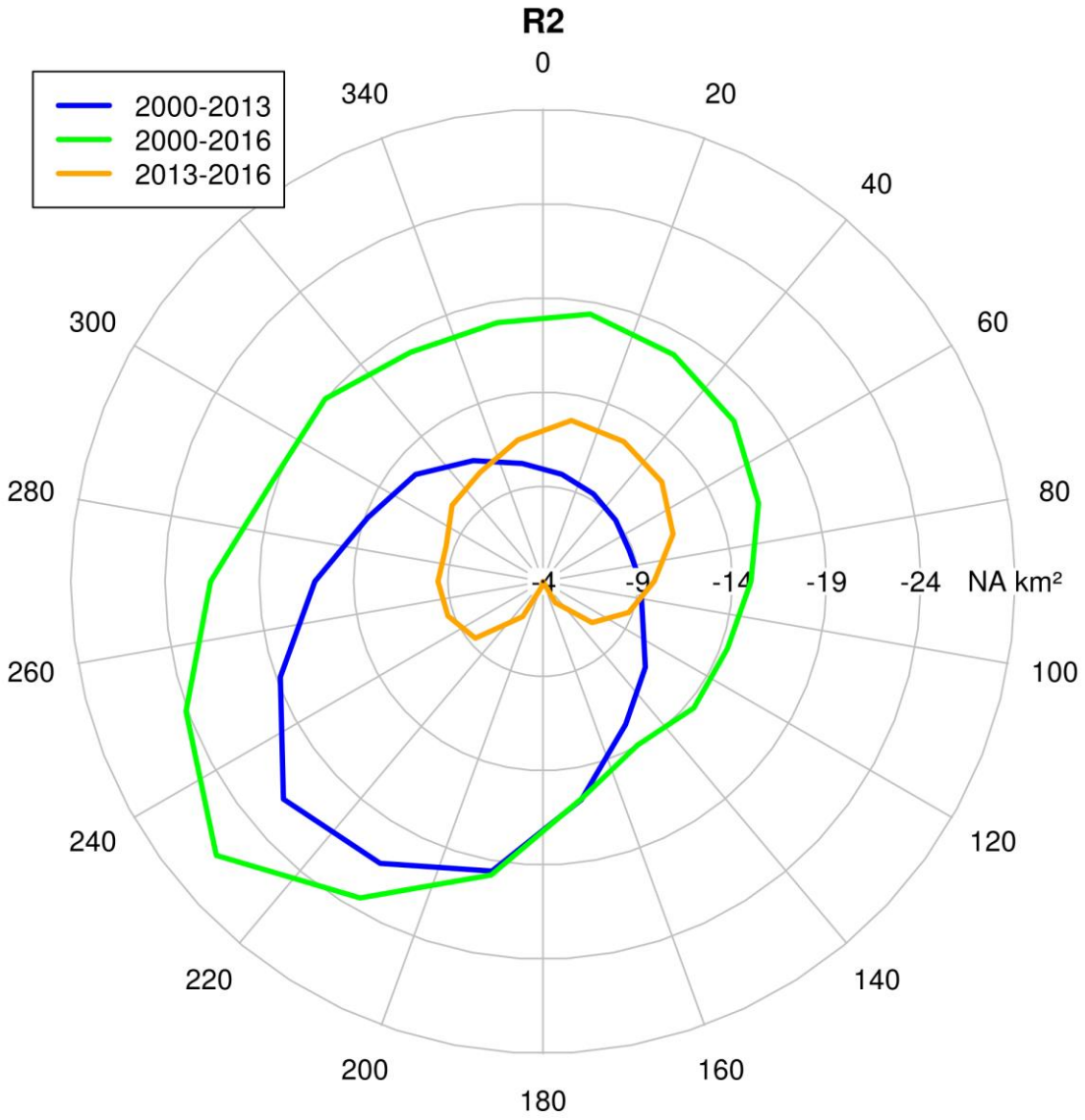

Figure S21. Polar plot of glacier area loss in subregion R2. The area losses are binned in aspect intervals of 20°.

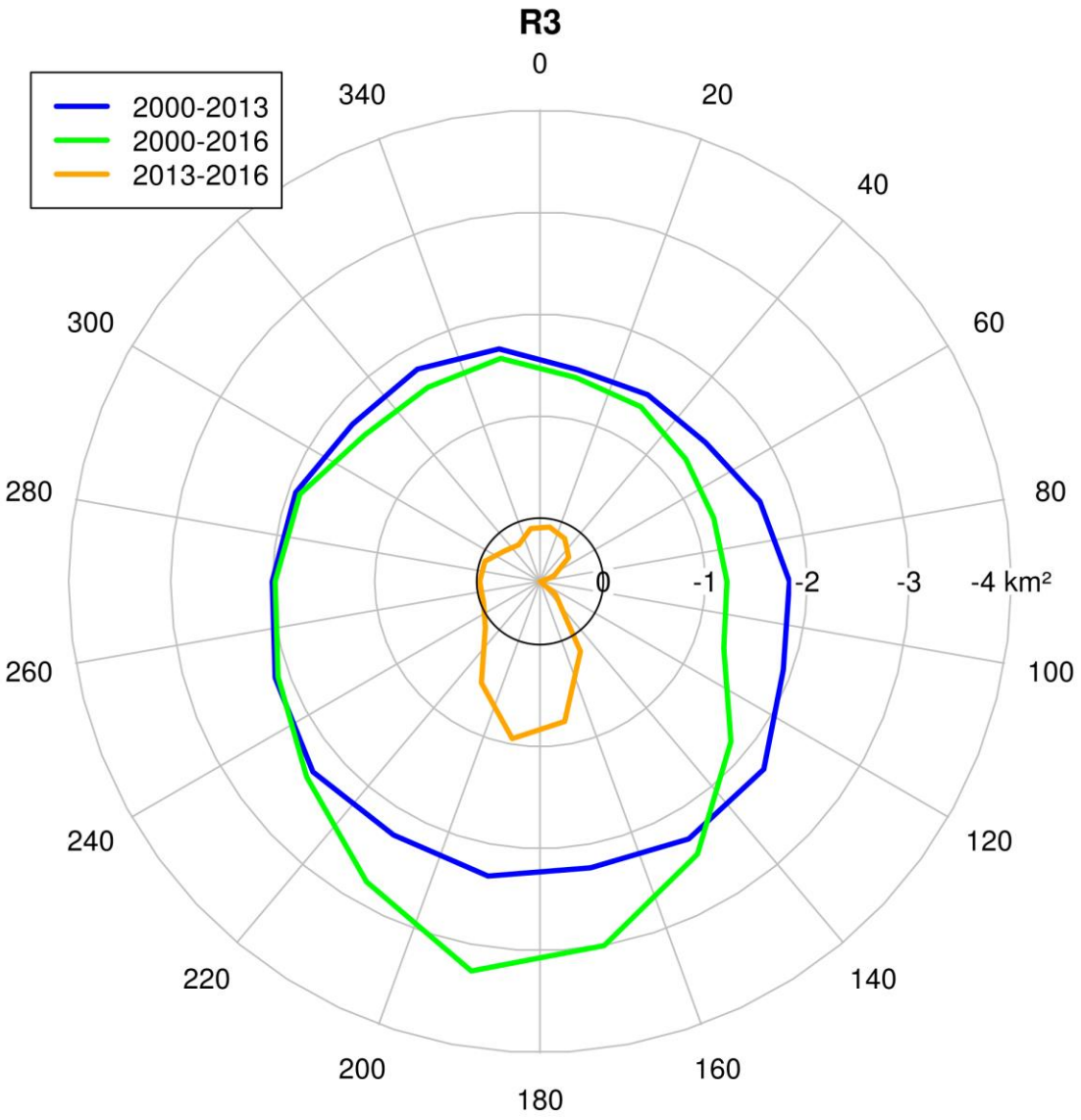

Figure S22. Polar plot of glacier area loss in subregion R3. The area losses are binned in aspect intervals of 20°.

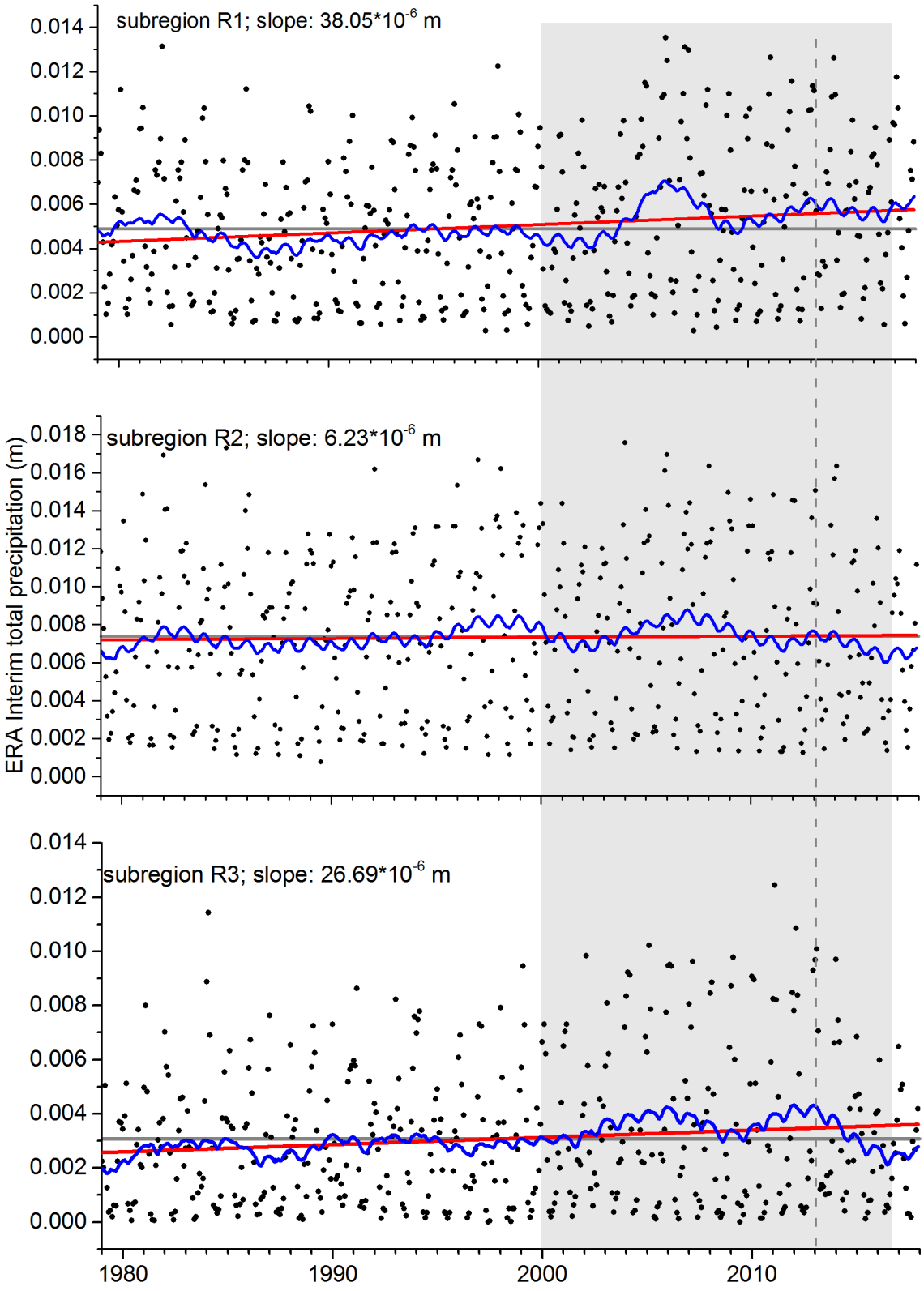

Figure S23. Total precipitation (monthly means of daily forecast accumulations) in the period 1979-2017 derived from ERA-Interim reanalysis data. Black dots: Spatial average values of glacier covered ERA-Interim grid cells in each subregion. Red line: long term trend (1979-2017), grey line: long term mean value; grey shaded area: period of mass budget and area change analysis, dashed grey line: marker for intermediate time step (early 2013)

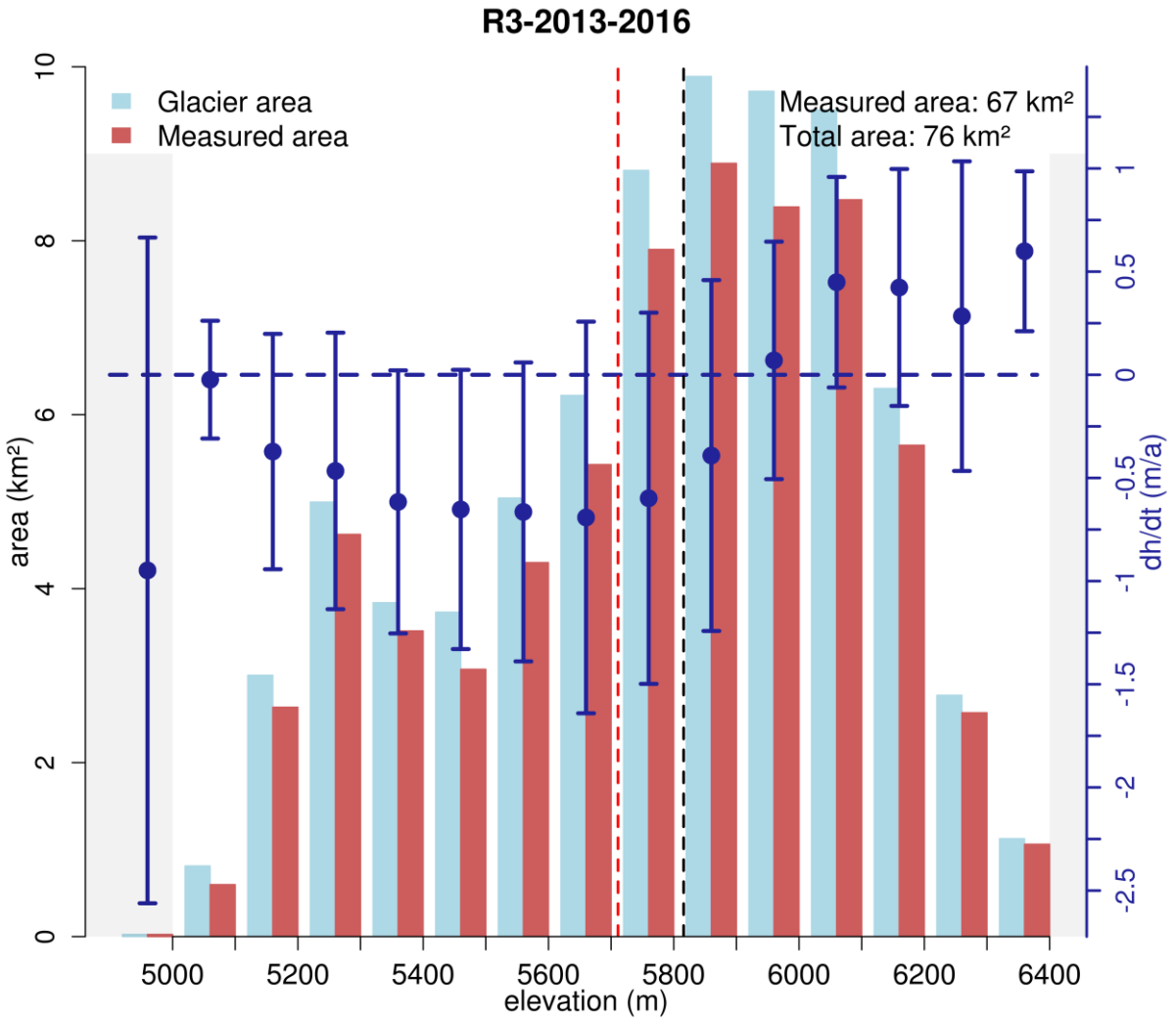

Figure S24. Hypsometric distribution of glacier area with elevation change (Δh/Δt) measurements (red) and total glacier area (light blue) in subregion R3 in the interval 2013-2016. Blue dots represent the mean Δh/Δt value in each elevation interval. Error bars indicate NMAD of Δh/Δt for each hypsometric bin. Grey areas mark the lower and upper 1% quantile of the glacier area distribution. Black dashed line: mean glacier elevation; Red dashed line: equilibrium line altitude (ELA), see also Table S3. Area measurements are based on the glacier outlines from 2013, considering only regions with slopes below applied slope threshold (50°, see Section 4.2)

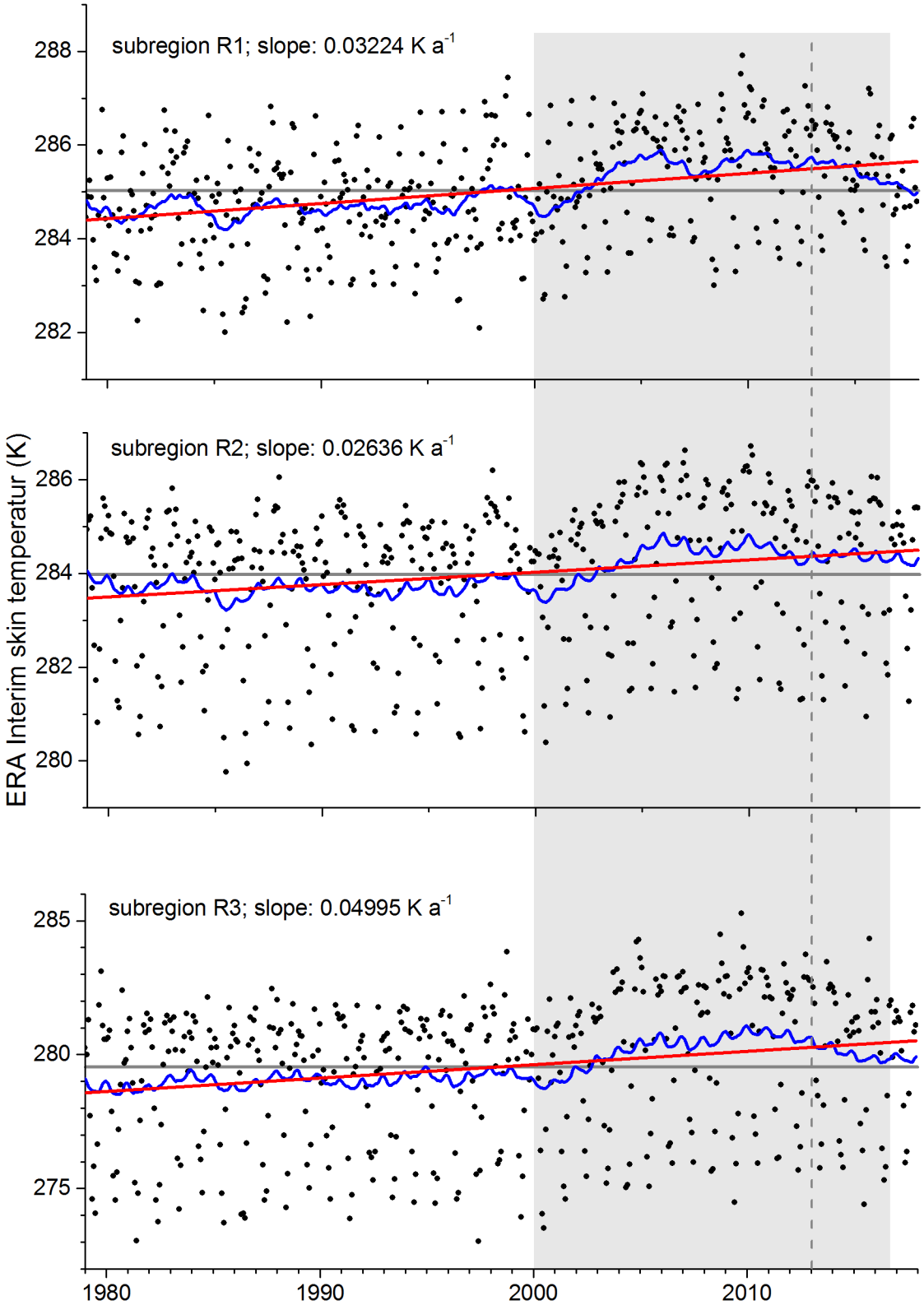

Figure S25. Skin temperature (monthly means of daily means) in the period 1979-2017 derived from ERA-Interim reanalysis data. Black dots: Spatial average values of glacier covered ERA-Interim grid cells in each subregion. Red line: long term trend (1979-2017), grey line: long term mean value; grey shaded area: period of mass budget and area change analysis, dashed grey line: marker for intermediate time step (early 2013)

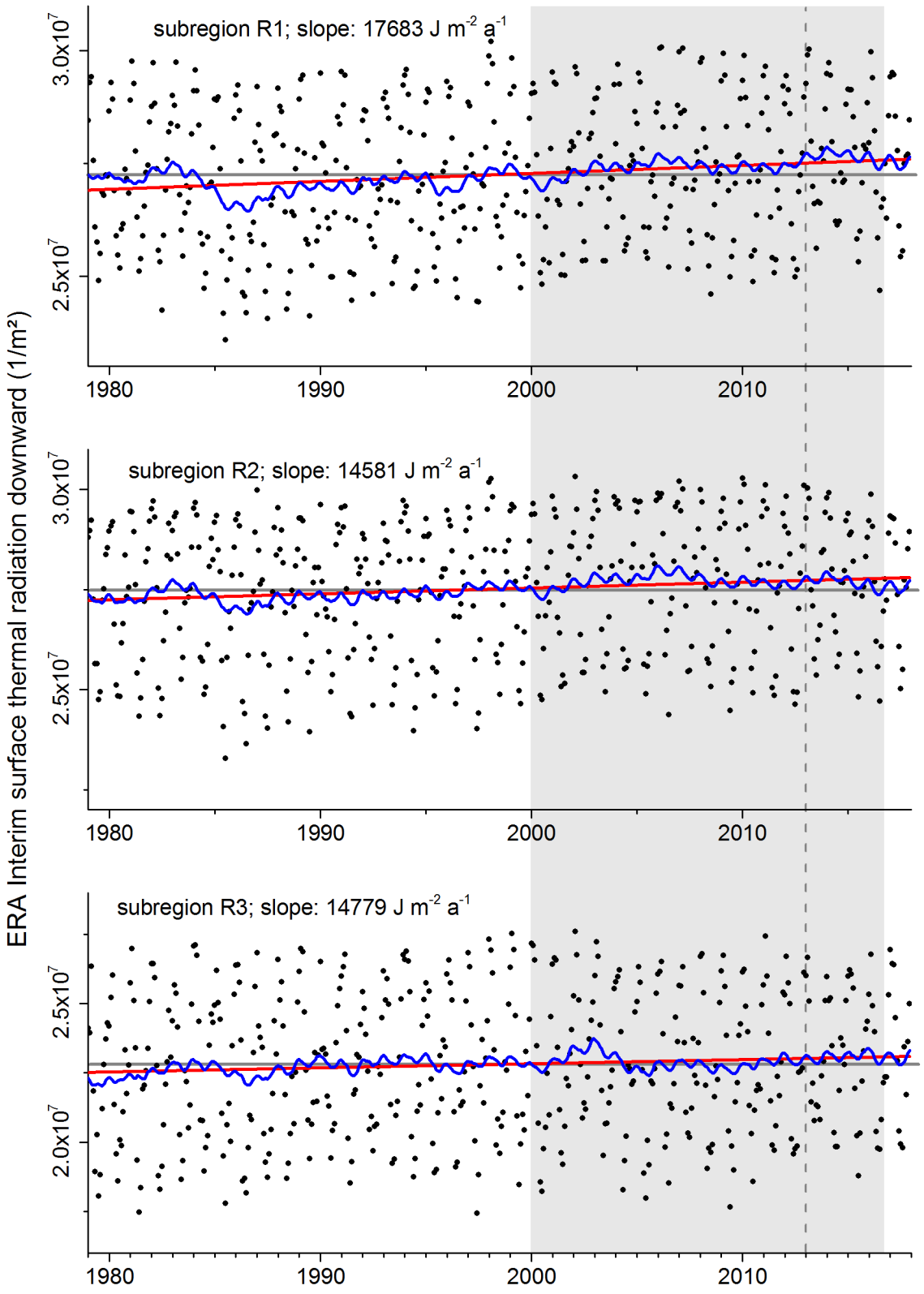

Figure S26. Surface thermal radiation downward (monthly means of daily forecast accumulations) in the period 1979-2017 derived from ERA-Interim reanalysis data. Black dots: Spatial average values of glacier covered ERA-Interim grid cells in each subregion. Red line: long term trend (1979-2017), grey line: long term mean value; grey shaded area: period of mass budget and area change analysis, dashed grey line: marker for intermediate time step (early 2013)

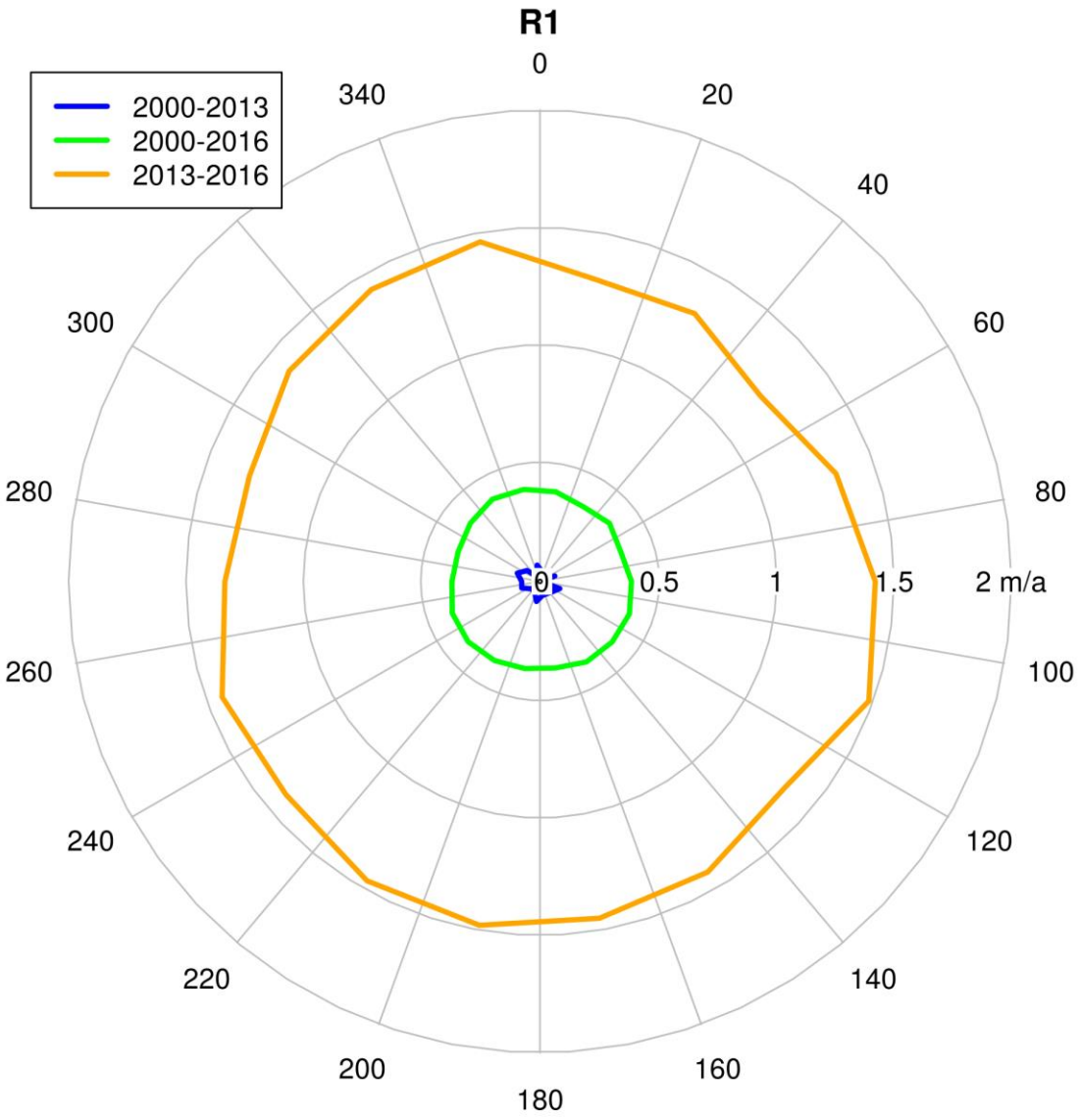

Figure S27. Polar plot of glacier surface lowering in subregion R1. The surface lowering measurements are averaged in aspect intervals of 20° (mean values).

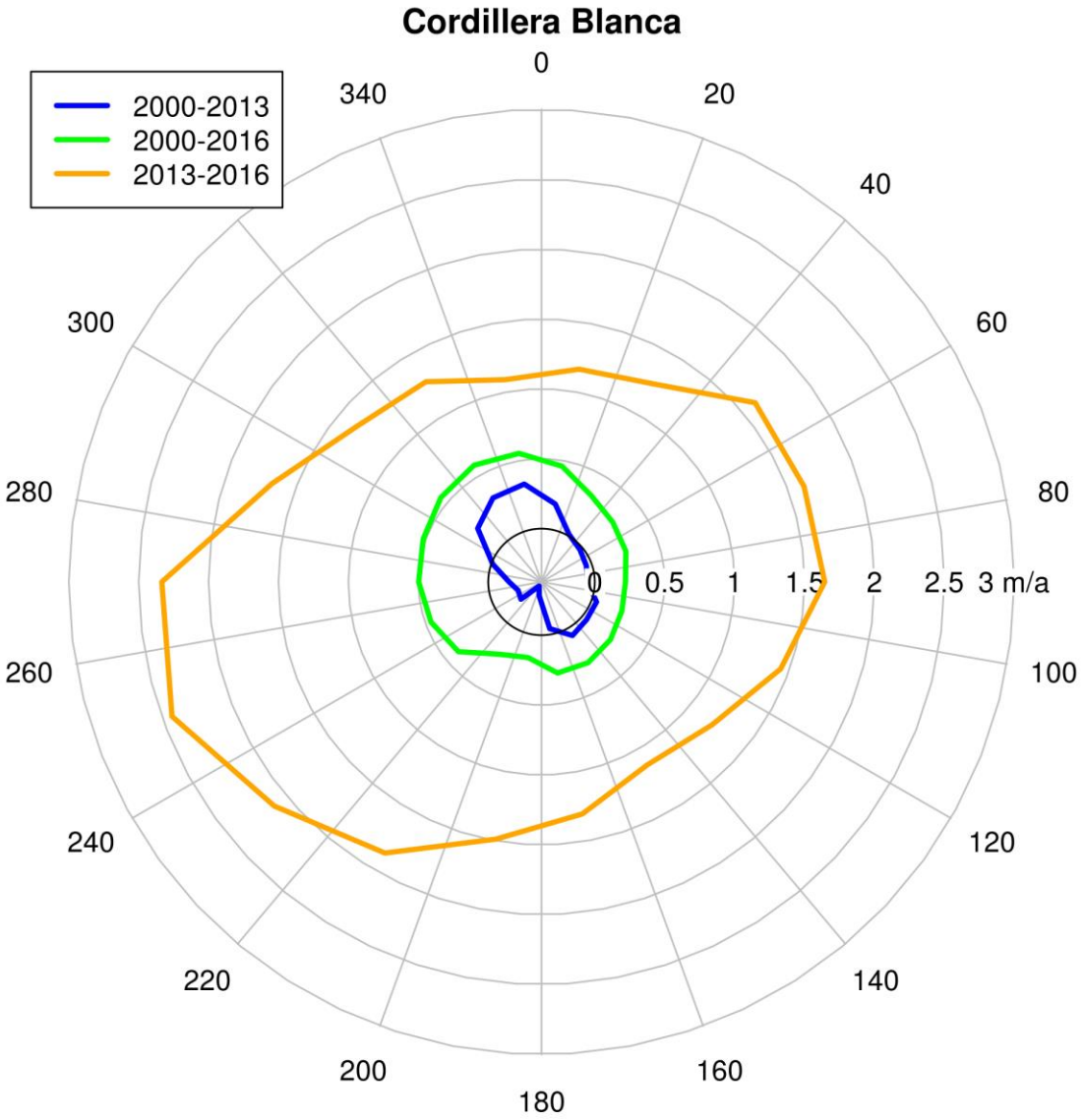

Figure S28. Polar plot of glacier surface lowering in Cordillera Blanca (subregion R1). The surface lowering measurements are averaged in aspect intervals of 20° (mean values).

Table S1. Overview of analysed TanDEM-X imagery for elevation change analysis (continued on next pages)

date	path	strip	path direction*	images
Subregion: R1 northern wet outer tropics				
2011-12-04	081	70	D	1
2011-12-25	066	60	D	1
2012-01-05	066	50	D	3
2012-01-06	081	80	D	2
2012-01-11	157	70	D	1
2012-01-16	066	20	D	2
2012-01-22	157	10	D	1
2012-01-22	157	10	D	3
2012-01-22	157	10	D	1
2012-01-27	066	30	D	3
2012-02-02	157	60	D	4
2012-02-07	066	40	D	2
2012-02-13	157	80	D	2
2012-02-18	066	10	D	2
2012-02-24	157	50	D	4
2012-03-01	081	90	D	1
2012-03-06	157	90	D	1
2012-03-06	157	20	D	1
2012-03-12	081	80	D	1
2012-03-17	157	30	D	3
2012-03-22	066	60	D	2
2012-03-23	081	60	D	1
2012-03-28	157	40	D	2
2012-03-28	157	40	D	2
2012-12-30	028	85	A	4
2013-01-10	028	75	A	6
2013-01-14	081	85	D	6
2013-01-21	028	65	A	4
2013-01-24	066	45	D	2
2013-01-27	119	55	A	1
2013-01-30	157	65	D	1
2013-02-01	028	55	A	5
2013-02-04	066	55	D	2
2013-02-05	081	65	D	1
2013-02-10	157	45	D	2
2013-02-12	028	45	A	1
2013-02-15	066	25	D	2
2013-02-21	157	35	D	2
2013-02-26	066	15	D	1
2013-03-01	119	45	A	1
2013-03-04	157	25	D	1
2013-03-12	119	35	A	2
2013-03-15	157	15	D	5
2013-03-23	119	25	A	7
2013-03-26	157	05	D	6
2016-09-08	119	10	A	4
2016-09-13	028	50	A	2
2016-09-16	066	10	D	2
2016-09-19	119	20	A	1
2016-09-27	066	20	D	2
2016-09-30	119	30	A	2
2016-10-08	066	40	D	2
2016-10-11	119	40	A	5
2016-10-14	157	40	D	1
2016-10-16	028	90	A	5
2016-10-19	066	50	D	2
2016-10-22	119	50	A	1
2016-10-22	119	50	A	2
2016-10-25	157	50	D	1
2016-10-27	028	60	A	2
2016-11-02	119	60	A	2
2016-11-16	157	60	D	1
2016-12-08	157	80	D	2
2016-12-19	157	90	D	2

Subregion: R2 southern wet outer tropics				
2012-12-18	005	75	D	1
2012-12-29	005	65	D	1
2012-12-31	043	85	A	2
2013-01-04	096	75	D	3
2013-01-09	005	85	D	1
2013-01-10	020	75	D	2
2013-01-11	043	75	A	3
2013-01-15	096	65	D	1
2013-01-15	096	65	D	1
2013-01-17	134	85	A	3
2013-01-20	005	45	D	1
2013-01-22	043	65	A	1
2013-01-26	096	85	D	2
2013-01-28	134	75	A	2
2013-01-31	005	55	D	1
2013-02-01	020	85	D	2
2013-02-02	043	55	A	1
2013-02-06	096	45	D	1
2013-02-08	134	65	A	1
2013-02-13	043	45	A	1
2013-02-17	096	35	D	1
2013-02-19	134	55	A	2
2013-02-22	005	15	D	2
2013-02-24	043	35	A	2
2013-02-28	096	25	D	2
2013-03-02	134	45	A	1
2013-03-07	043	25	A	2
2013-03-11	096	15	D	2
2013-03-13	134	35	A	2
2013-03-16	005	05	D	2
2013-03-22	096	05	D	3
2013-03-24	134	25	A	3
2013-03-27	005	40	D	1
2013-04-02	096	70	D	1
2013-04-07	005	75	D	1
2013-04-18	005	10	D	2
2016-09-07	096	80	D	2
2016-09-09	134	20	A	2
2016-09-12	005	10	D	2
2016-09-13	020	90	D	1
2016-09-14	043	30	A	1
2016-09-18	096	10	D	1
2016-09-20	134	10	A	3
2016-09-29	096	20	D	1
2016-10-01	134	30	A	2
2016-10-04	005	40	D	1
2016-10-12	134	40	A	2
2016-10-15	005	50	D	1
2016-10-21	096	30	D	2
2016-10-23	134	50	A	3
2016-11-18	020	80	D	1
2016-11-28	005	60	D	1
2016-12-20	005	70	D	2
2016-12-26	096	70	D	2
Subregion: R3 dry outer tropics				
2012-12-02	096	15	D	1
2012-12-07	005	10	D	1
2012-12-29	005	65	D	1
2012-12-29	005	65	D	1
2012-12-31	043	85	A	1
2013-01-09	005	85	D	2
2013-01-11	043	75	A	4
2013-01-16	119	85	A	2
2013-01-20	005	45	D	3
2013-01-22	043	65	A	1
2013-01-22	043	65	A	2
2013-01-31	005	55	D	3
2013-02-02	043	55	A	2

2013-02-07	119	75	A	2
2013-02-13	043	45	A	4
2013-02-19	134	45	A	1
2013-02-24	043	35	A	3
2013-03-02	134	35	A	1
2013-03-07	043	25	A	2
2013-03-10	081	25	D	2
2013-03-13	134	25	A	2
2013-03-18	043	15	A	2
2013-03-21	081	15	D	2
2013-03-24	134	15	A	2
2013-04-02	096	70	D	2
2013-04-13	096	55	D	2
2013-04-24	096	45	D	2
2014-01-04	134	05	A	2
2014-01-15	134	15	A	2
2014-01-26	134	25	A	2
2014-03-09	096	50	D	2
2014-03-20	096	60	D	3
2016-09-07	096	10	D	1
2016-09-08	119	70	A	2
2016-09-09	134	10	A	2
2016-09-12	005	20	D	1
2016-09-14	043	20	A	1
2016-09-20	134	20	A	4
2016-09-23	005	30	D	2
2016-09-29	096	20	D	1
2016-09-30	119	80	A	1
2016-10-01	134	30	A	2
2016-10-04	005	40	D	2
2016-10-11	119	90	A	1
2016-10-12	134	40	A	1
2016-10-15	005	50	D	3
2016-10-21	096	30	D	2
2016-11-28	005	60	D	1
2016-12-26	096	80	D	1

*A – ascending, D – descending

Table S2. Overview of analysed Landsat imagery for glacier area mapping

Date	Path	row
Subregion: R1 northern wet outer tropic		
2000-09-09	6	68
2000-09-09	6	69
2000-08-15	7	67
2000-08-15	7	68
2000-07-21	8	66
2000-07-21	8	77
2013-06-16	7	67
2013-06-16	7	68
2013-07-09	8	66
2013-07-09	8	67
2013-07-11	6	68
2013-07-11	6	69
2013-08-19	7	67
2014-07-12	8	66
2014-07-12	8	67
2014-07-14	6	68
2014-08-22	7	67
2014-11-19	6	69
2014-11-26	7	68
2016-01-16	7	68
2016-01-16	7	69
2016-06-15	8	66
2016-06-15	8	67
2016-06-17	6	68
2016-07-10	7	67
Subregion: R2 southern wet outer tropic		
2000-06-23	4	69
2000-07-18	3	69
2000-07-18	3	70
2000-08-17	5	69
2000-08-28	2	70
2013-06-27	4	69
2013-06-29	2	70
2013-07-22	3	70
2014-06-05	5	69
2016-07-21	4	69
2016-07-23	2	70
2016-07-30	3	70
2016-08-29	5	69
Subregion: R3 dry outer tropics		
2000-07-25	4	70
2000-07-16	5	70
2000-08-03	3	71
2000-09-11	4	71
2000-09-13	2	71
2013-09-06	5	70
2013-09-08	3	71
2013-09-01	2	71
2013-09-15	4	70
2013-10-17	4	71
2016-05-11	3	71
2016-05-20	2	71
2016-07-28	5	70
2016-07-21	4	70
2016-07-21	4	71

Table S3: Snow line altitude (SLA) and equilibrium line altitude (ELA) reported for the study region and period. (RS: remote sensing, GL: glaciological method, AA: Area-Altitude method, H_{mean}: mean glacier elevation). Bold values indicate used average ELA for penetration depth bias estimation.

period	min (m a.s.l.)	max (m a.s.l.)	Type	Method	Source
Subregion R1					
2000-2015	4845	5085	SLA	RS	Veettil et al., 2017a
2000-2015	4720	4920	SLA	RS	Veettil et al., 2017b
1999-2005	5034	5086	SLA	RS	McFadden et al., 2011
2006-2010	4835	5075	SLA	RS	Lopez-Moreno et al., 2014
2006-2008	4953	4985	ELA	GL	Gurgiser et al., 2013
2004-2015	4959	5071	ELA	GL	Artesonraju Glacier, WGMS
2004-2015	4868	4942	ELA	GL	Yanamarey Glacier, WGMS
	average: 4955				
Subregion R2					
2000-2015	4680	5120	SLA	RS	Veettil et al., 2017b
1998-2009	5526	5414	SLA	RS	Hanshaw and Bookagen, 2014
1998-2016	5050	5414	ELA	H_{mean}	Drenkhan et al. 2018
	average: 5199				
Subregion R3					
2000-2014	5480	5745	SLA	RS	Veettil et al., 2016
2007	5910		ELA	AA	Ubeda, 2011
	average: 5711				

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