S 1 Point mass balance modeling

The set of model parameters was optimized applying a Monte-Carlo model optimization performing 1000 runs for the period October 1st, 2003 to September 30th, 2013. The best model run was identified by validating the model results against readings at stake 22. Figure S1 shows the results of the 1000 model runs and the stake readings which were used to identify the best model parameter setting.

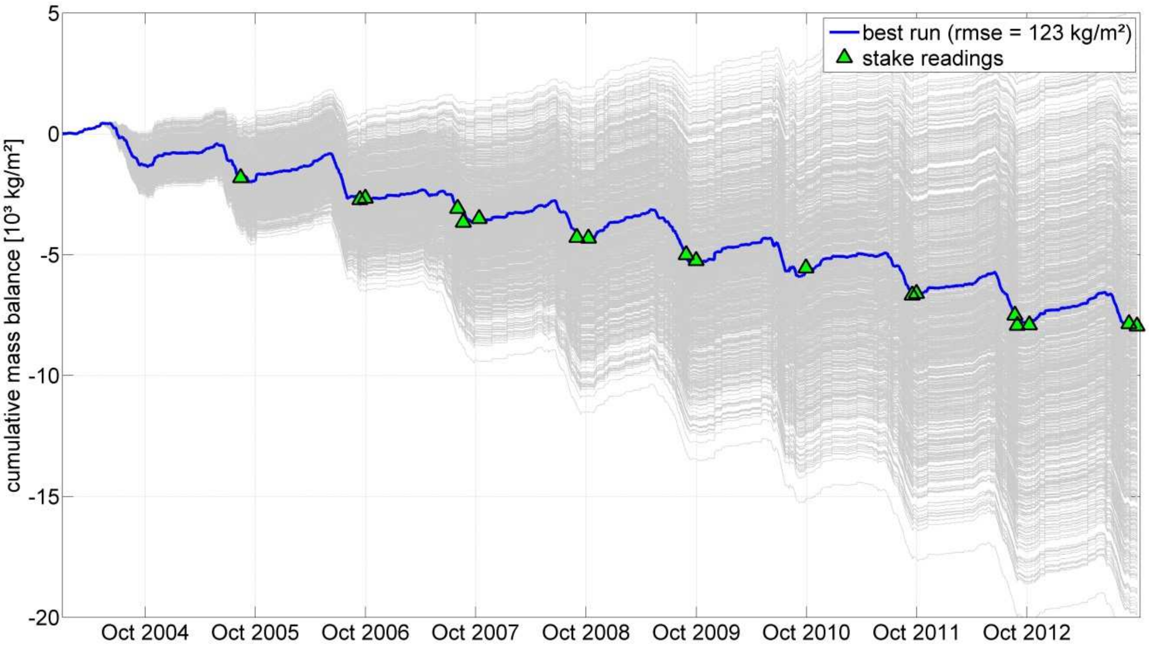

Figure S1. *Series of cumulative mass balance obtained from 1000 Monte-Carlo runs during the model optimization and measured cumulative point mass balance at stake 22 which was used to identify the best run and hence the optimal parameter set.*

Precipitation scaling factors were derived fitting the mass balance model to meet the observed / estimated date of the emergence of last year's reference surface (i.e. when the snow pack of the previous accumulation season has melted entirely). For some years and locations this was not possible, especially not for stake 24, which is located in a north exposed slope at an altitude of about 3270 m a.s.l. Even in years with very negative mass balance, this point may be subject to positive mass balance. Hence, the presented way of tuning the model did not work for this location. Nevertheless, mass balance information of this point was important for the reanalysis since no observations of that glacier part were available for the period 2004 to 2008. For that reason we calculated mass balances for this location applying the following procedure:

First we calculated a series of perfect Γ_i for the years 2009 to 2013 by fitting the model to the measured mass balances $\pm$ 10 kg m^{-2} at this location. The same was done for the location of stake 31 which has a similar setting in terms of aspect and altitude and is located only 300 m southwest of stake 24. We calculated a linear regression between the two series of relative anomalies of the resultant five-year series of Γ_i. This regression was subsequently used to derive relative Γ_i -anomalies for 2004 to 2008 at stake 24. Applying those to the average Γ_i of stake 24 (2009 to 2013) results in a complete series of Γi at stake 24 for the whole observation period.

Table S1. *Dates of emergence of last year's reference surface.*

Year	*Stake* 20	*Stake* 21	*Stake* 22	*Stake* 23	*Stake* 24	*Stake* 25	*Stake* 29	*Stake* 30	*Stake* 31	*Stake* 33
2004	08.03.	07.28.	08.05.	09.05.		08.05.	08.01.	08.13.	08.20.	08.10.
2005	07.04.	06.22.	07.20.	07.31.		06.25.	07.04.	07.17.	07.25.	07.30.
2006	07.20.	07.04.	07.20.	09.05.		07.15.	07.15.	07.20.	07.25.	07.25.
2007	07.18.	07.20.	07.23.	09.15.		07.31.	07.15.	07.29.	08.05.	08.01.
2008	07.06.	07.25.	08.10.	09.12.		08.15.	07.31.	08.06.	09.03.	08.05.
2009	08.09.	08.01.	08.10.			08.20.	08.05.	08.15.	08.29.	08.20.
2010	08.26.	07.05.	07.15.			07.16.	07.20.	08.28.		08.25.
2011	08.25.	08.05.	08.20.			08.20.	08.23.	08.23.	09.10.	08.25.
2012	08.05.	07.01.	07.25.	08.20.		07.01.	07.19.	07.25.	08.01.	08.01.
2013		08.05.	08.18.				08.13.			

Table S2. *Precipitation scaling factors as used to create pseudo observations of point mass balance.*

Year	*Stake* 20	*Stake* 21	*Stake* 22	*Stake* 23	*Stake* 24	*Stake* 25	*Stake* 29	*Stake* 30	*Stake* 31	*Stake* 33
2004	2.0	1.7	1.8	2.7	3.4*	1.4	2.7	2.3	2.6	4.0
2005	2.0	1.3	2.3	2.6	2.3*	1.2	2.3	2.1	2.0	3.5
2006	3.0	1.6	2.8	3.6	3.0*	1.9	2.8	2.6	2.4	3.9
2007	2.9	2.6	2.6	3.1	2.8*	2.1	3.3	2.5	2.3	4.7
2008	1.8	1.9	2.8	3.6	4.3*	2.2	3.2	2.4	3.1	3.9
2009	2.6	2.1	2.4	3.2[1]	3.0[1]	2.0	2.7	2.3	2.4	3.6
2010	3.5	1.7	2.5	2.8[1]	3.8[1]	2.1	3.4	3.1	3.0[1]	4.2
2011	2.7	1.6	2.0	2.8[1]	2.5[1]	1.2	3.3	2.0	2.0	3.6
2012	3.8	1.6	2.6	4.2	3.5[1]	1.1	3.2	2.4	2.5	4.2
2013	2.8[1]	1.8	2.2	2.1[1]	2.6[1]	2.6[1]	2.7	2.3[1]	2.5[1]	3.3[1]

[1] *perfect* $\Gamma_{i,a}$ (fitted to measured annual point mass balance). * $\Gamma_{i,a}$ derived from linear regression with Γ_i-series from nearby stakes

Table S3. *Modeled point mass balance [kg m^{-2}].*

Year	*Stake* 20	*Stake* 21	*Stake* 22	*Stake* 23	*Stake* 24	*Stake* 25	*Stake* 29	*Stake* 30	*Stake* 31	*Stake* 33
2004										
2005										
2006										
2007	−1298	−1011	−881							
2008	−1799	−1288	−834			−323				
2009			−835	192	500					
2010	5	−979	−313	328	889		−611		350	−189
2011	−711	−1464	−1055	−364	106	−985	−834	−808	−278	−1101
2012	−819	−1949	−1300	−225	−51	−1602	−1873	−1265	−855	−1199
2013	184	−514	−15	380	707	113	−328	95	403	11

Table S4. *Measured point mass balance [kg m^{-2}].*

Year	*Stake* 20	*Stake* 21	*Stake* 22	*Stake* 23	*Stake* 24	*Stake* 25	*Stake* 29	*Stake* 30	*Stake* 31	*Stake* 33
2004										
2005										
2006										
2007	−1298	−1011	−881							
2008	−1799	−1288	−834			−323				
2009			−835	192	500					
2010	5	−979	−313	328	889		−611		350	−189
2011	−711	−1464	−1055	−364	106	−985	−834	−808	−278	−1101
2012	−819	−1949	−1300	−225	−51	−1602	−1873	−1265	−855	−1199
2013	184	−514	−15	380	707	113	−328	95	403	11

S 2 Uncertainty assessment

S 2.1 Uncertainties in glaciological mass balances

Uncertainty sources and respective values as applied in this study are shown in Table S5. For the uncertainty assessment procedure, we assigned uncertainty values to each point measurement (stakes, pits, probings) individually as some of them are dependent on year and location. Tables with measurements and individual uncertainties are currently being prepared to be published in an appropriate online-repository.

Table S5. *Overview of uncertainties related to our study and their origin.*

point scale				
Source	**random**		**systematic**	
stake	reading	0,03 m	tilted stakes (negative bias)	< 3%
	surface roughness	0,1 to 0,3 m		
snow pits	reading errors snow depth	0,03 m		
	bulk density measurement errors	15 kg/m³		
	reference surface & snow corrections	50 kg/m²		
snow probings	extrapolated density	20 kg/m³	tilted probings (positive bias)	< 3%
	reading errors snow depth	0,02 m		
glacier scale				
Source	**random**		**systematic**	
stake				
snow pits				
snow probings	propagation of point errors	9 to 26 kg/m²	propagation of point errors	< 2%
extrapolation	inherent uncertainty of method	< 56 kg/m²	can hardly be quantified -> geodetic cross check	
reference area	uncertainties in current glacier extent	< 20 kg/m²	missing updates	< 1%

Uncertainties for each year and season were calculated individually (Table S6). The effect of point scale uncertainties on mean specific mass balances strongly depends on the amount of measurements since random errors cancel out each other if the amount of measurements is large. The spatial distribution of measurements also plays a role. Therefore we applied a bootstrap approach calculating each individual annual and seasonal mass balance 5000 times using the inverse distance method which was relatively easy to automatize. In every calculation a random error (according to a defined normal distribution corresponding to the assigned random uncertainty of the individual point) was added to each individual point measurement. The standard deviation of the 5000 resultant glacier wide mass balance values was then used as the random uncertainty related to point measurements.

Uncertainties due to the extrapolation of point measurements to the glacier scale were derived analyzing the output of five different extrapolation approaches. For summer balances we corrected all ten-year mass balance series of the reanalysis for their individual bias compared to the reference series. Then we used the absolute range of the bias corrected balance series as the uncertainty range for the respective year. For winter balances we omitted the bias correction since winter balance biases were much smaller and could not clearly be explained.

Uncertainties related to inaccurate glacier outlines are small in our study since we adapted the glacier extent (and altitudinal bands) for each year. We estimated the remaining uncertainties of the re-analyzed series as $\pm$ 15 kg m^{-2} for all years except for the year 2004, for which we apply a more conservative estimate of $\pm$ 25 kg m^{-2} due to additional uncertainties in the glacier outline of that year. For winter balances the effect of inaccurate glacier outlines on mean specific balances is smaller due to small spatial gradients in winter balance.

Table S6. *Number of point measurements (N), reanalyzed mass balance and respective random errors for different years and seasons.*

Annual						
$Year$	N	B_{ref}	$\sigma_{glac.point.a}$	$\sigma_{glac.spatial.a}$	$\sigma_{glac.ref.a}$	$\sigma_{glac.total.a}$
		kg m^{-2}	kg m^{-2}	kg m^{-2}	kg m^{-2}	kg m^{-2}
2004	32	−1140	25	28	15	41
2005	33	−1456	25	47	25	59
2006	30	−1514	26	23	15	38
2007	30	−1540	26	124	15	127
2008	32	−1320	22	134	15	136
2009	30	−944	24	55	15	62
2010	28	−494	18	79	15	82
2011	29	−1167	19	87	15	90
2012	28	−1556	23	39	15	47
2013	100	−247	11	24	15	31
$mean$	37	−1138	22	75	16	80

Winter						
$Year$	N	B_{ref}	$\sigma_{glac.point.a}$	$\sigma_{glac.spatial.a}$	$\sigma_{glac.ref.a}$	$\sigma_{glac.total.a}$
2004	22	1022	16	95	5	97
2005	87	750	7	48	10	50
2006	47	925	10	38	5	40
2007	48	558	7	43	5	44
2008	36	814	10	45	5	46
2009	61	1267	14	31	5	34
2010	80	843	8	56	5	56
2011	127	965	7	33	5	34
2012	58	932	10	52	5	53
2013	109	1216	9	31	5	32
$mean$	68	929	10	50	6	52

Summer						
$Year$	N	B_{ref}	$\sigma_{glac.point.a}$	$\sigma_{glac.spatial.a}$	$\sigma_{glac.ref.a}$	$\sigma_{glac.total.a}$
2004		−2162	30	99	16	105
2005		−2206	26	68	27	77
2006		−2439	28	45	16	55
2007		−2098	27	131	16	134
2008		−2134	24	141	16	144
2009		−2211	27	63	16	71
2010		−1337	19	96	16	99
2011		−2132	20	93	16	96
2012		−2488	25	65	16	71
2013		−1463	14	39	16	44
$mean$		−2067	25	90	17	95

S 2.2 Uncertainties in geodetic mass balances.

Uncertainties in geodetic mass balances are governed by the assumptions related to the conversion of observed volume changes to changes in mass, except for the period 2011 to 2013 when the effect of remaining uncertainties in the digital terrain models exceeds the uncertainties related to the density assumption. Table S7 shows the assumed random errors and their sources for the three geodetic balance periods of this study.

Table S7. *Geodetic mass balances and respective random uncertainties for all investigated (sub-) periods.*

$Period$	$B_{geod.corr}$	$\sigma_{geod.total}$	σ_{dc}	σ_{sc}	σ_{sd}	$\sigma_{geod.corr}$
2005 - 2013	-9644	180	671	100	100	709
2005 - 2011	-7436	180	511	100	100	560
2011 - 2013	-2084	180	95	100	100	248