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Supplement of

Black carbon in snow in the upper Himalayan Khumbu Valley, Nepal: observations and modeling of the impact on snow albedo, melting, and radiative forcing

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Supplement

The supplement includes ten figures (S1a, S1b, S1c, S2a, S2b, S3a, S3b, S4, S5, and S6) and three tables (S1, S2, and S3).
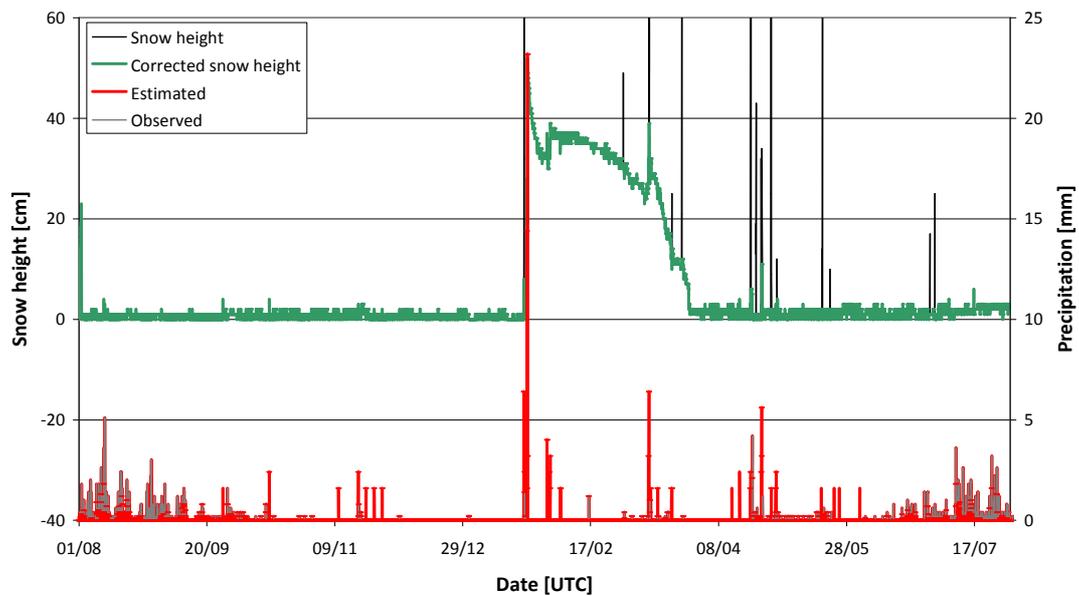
Figure S1a. Time series of recorded and corrected snow height (left axis) and precipitation (right axis) at NCO-P for the winter season 2004/05. The green line indicates the corrected snow height after removal of the recorded individual peaks (black lines). Maximum recorded snow height was 200 cm. The red line corresponds to the corrected time series of precipitation in comparison to the recorded precipitation (grey line). Horizontal red bars indicate solid precipitation.
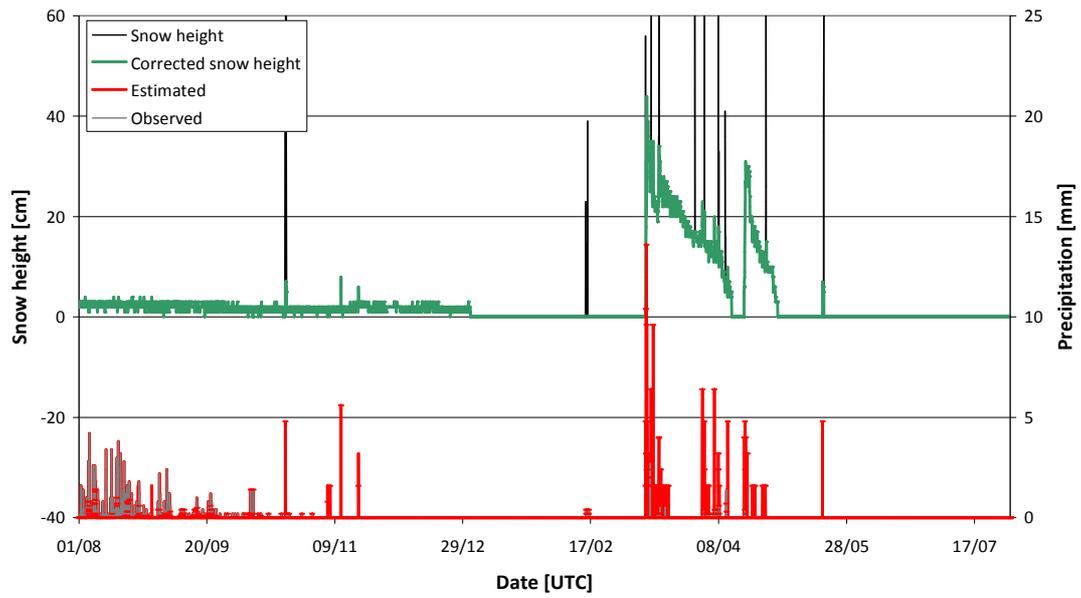
Figure S1b. Same as Figure S1a, but for 2005/06. Maximum recorded snow height was 177 cm.
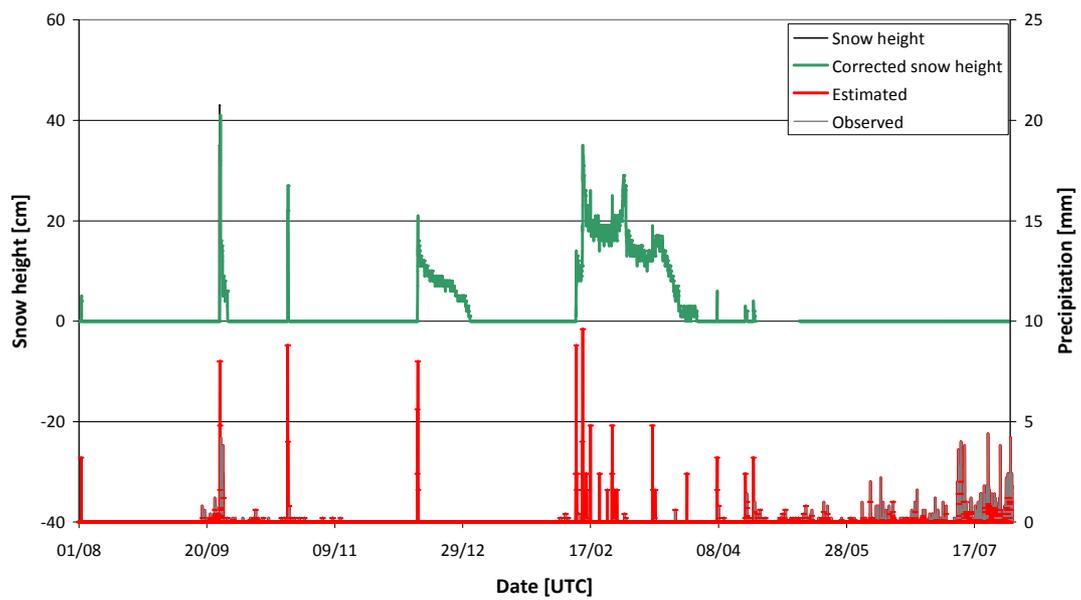
Figure S1c: Same as Figure S1a, but for 2006/07.
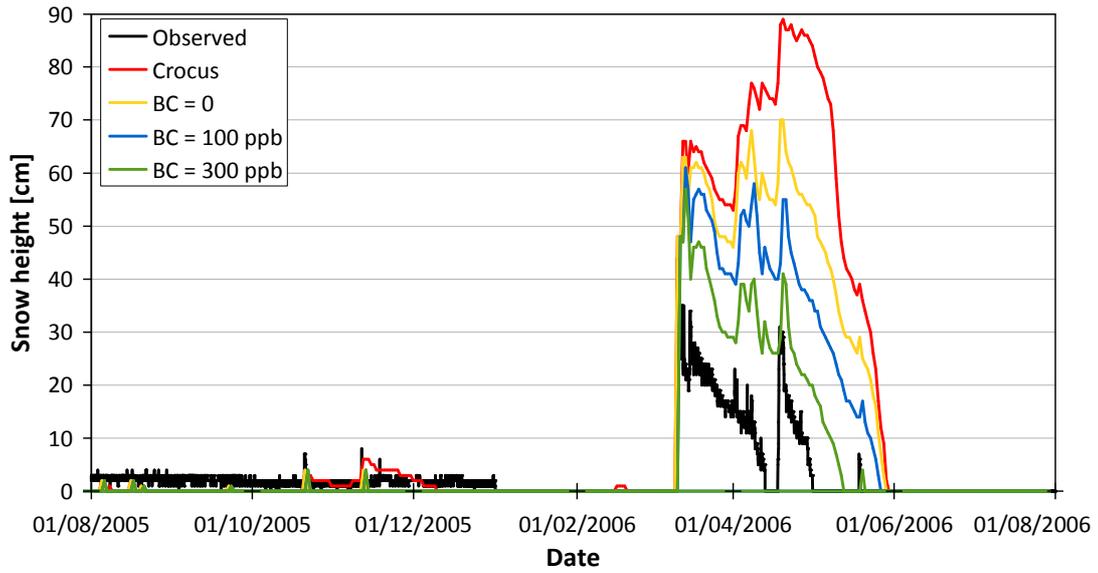
Figure S2a. Comparison of observed (black) and simulated snowpack heights at NCO-P for the winter season 2005/06. Simulations were performed with the standard Crocus model (red) and with the upgraded model including radiative transfer with constant BC concentrations of 0 (yellow), 100 (blue), and 300 ppb (green).
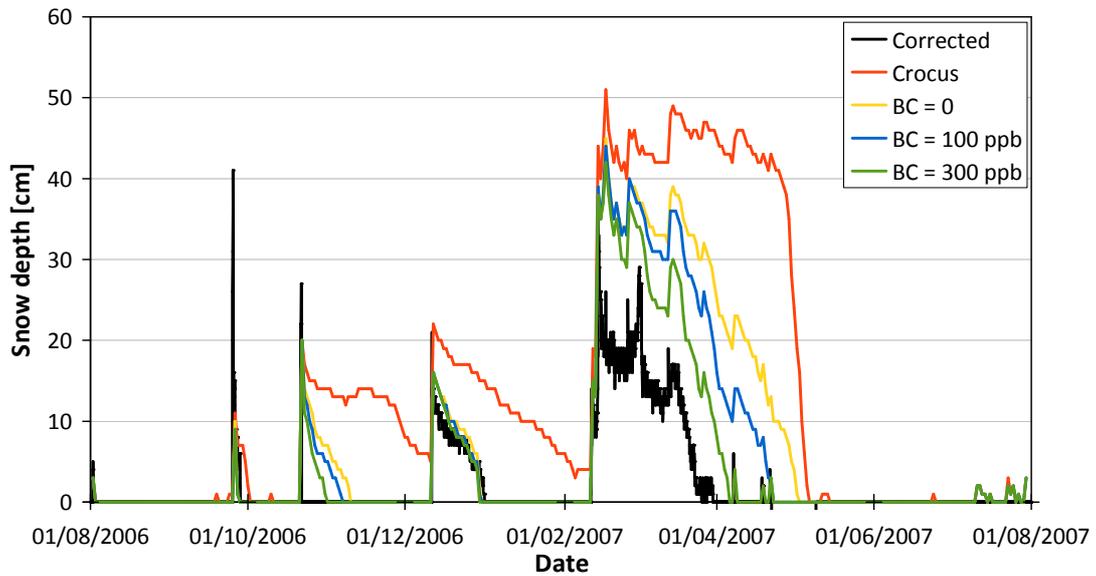
Figure S2b. Same as Figure S2a, but for 2006/07.
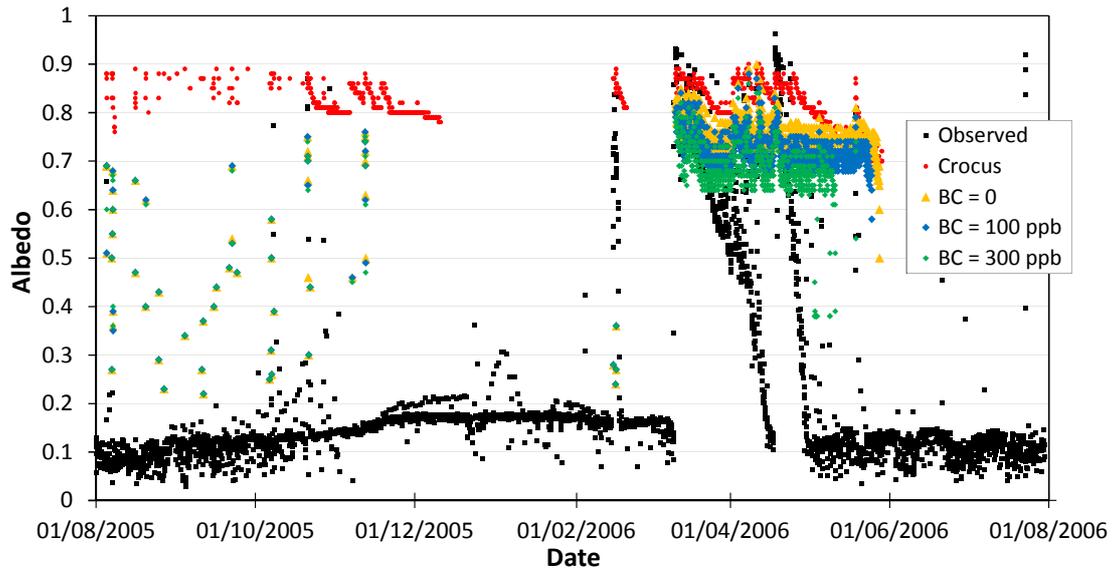
Figure S3a. Comparison of observed (black) and simulated albedo at NCO-P for the winter season 2005/06. Simulations were performed with the standard Crocus model (red) and with the upgraded model including radiative transfer with BC concentrations of 0 (yellow), 100 (blue), and 300 ppb (green).
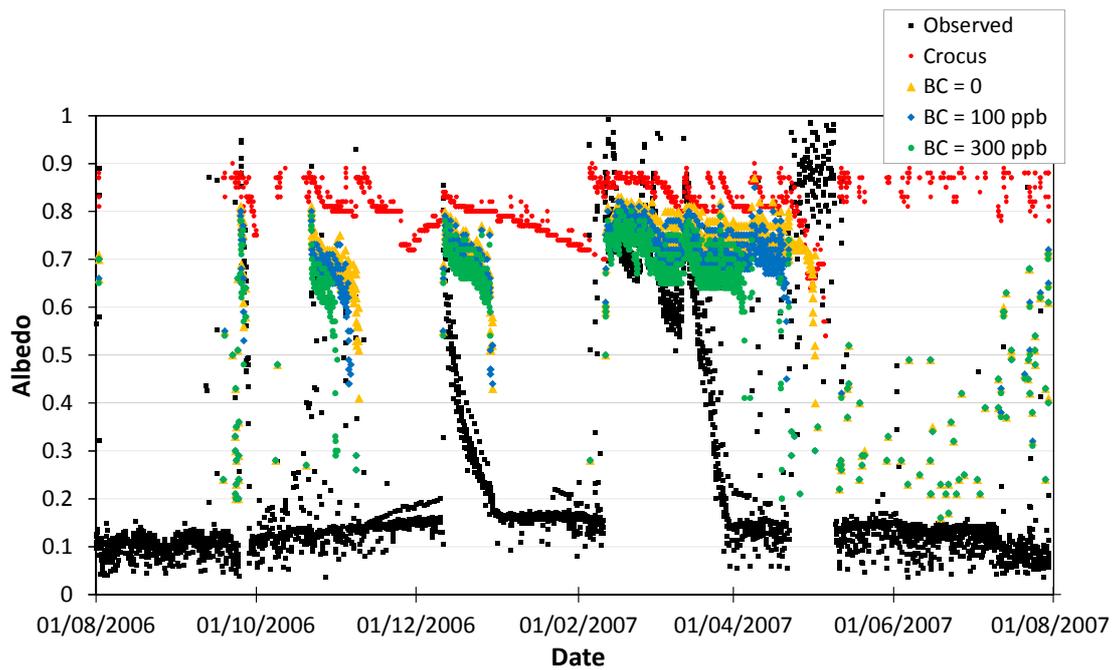
Figure S3b. Same as Figure S3a, but for 2006/07.
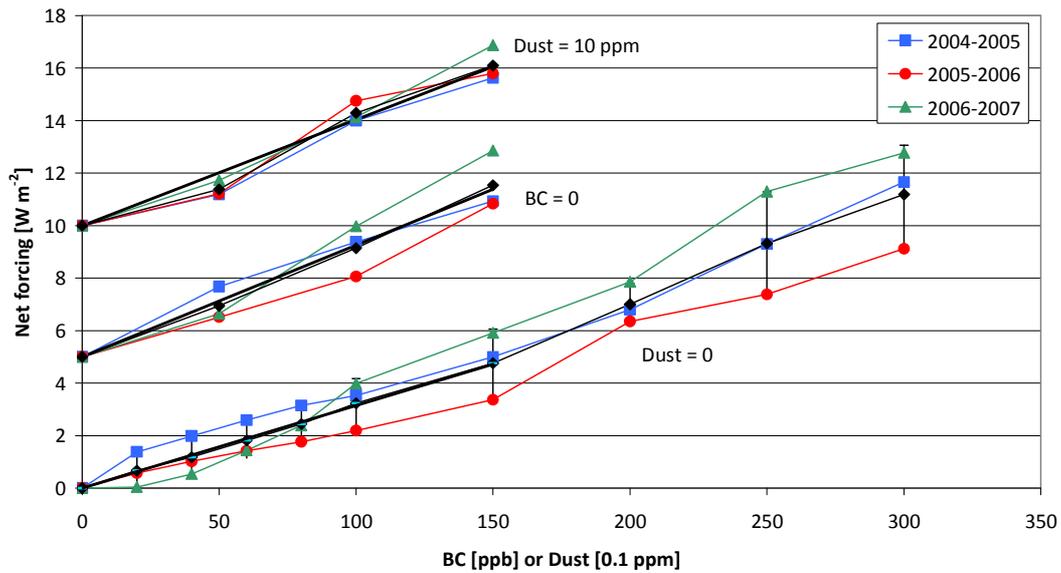
Figure S4. Simulated annual net forcing related to shortwave radiation and latent and sensible heat fluxes due to the presence of BC and dust in the snow. Simulations are performed without dust, without BC (shifted by +5 W m^{-2}), and with dust = 10 ppm (shifted by +10 W m^{-2}). In the last case, the reductions are calculated relative to the case with BC = 0 and dust = 10 ppm. Black symbols indicate the 3-yr averages of the net forcing with the error bars representing the standard deviation. Black lines correspond to results of linear regressions forced through the origin for all average values for BC ≤ 150 ppb.
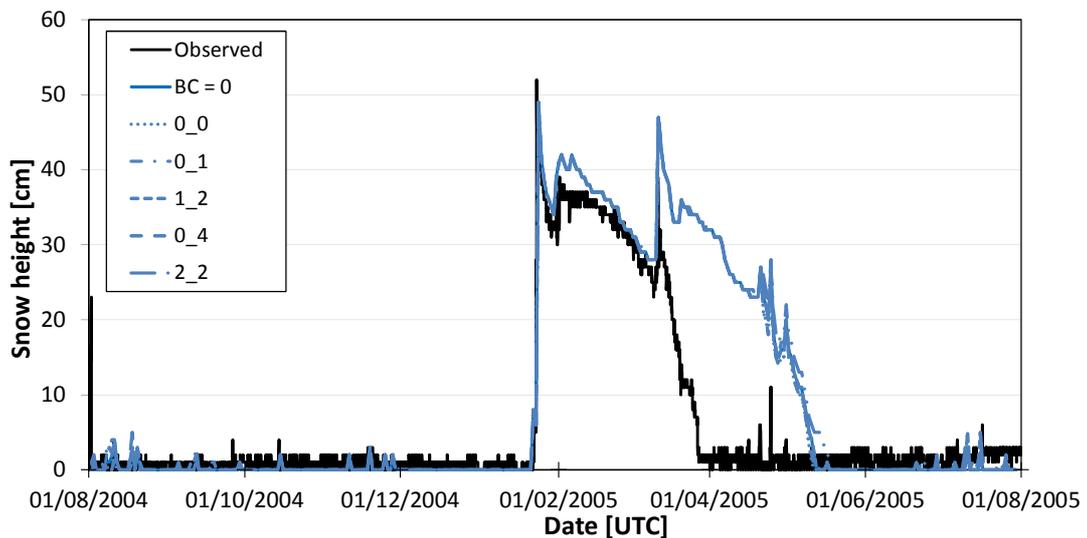
Figure S5. Comparison of observed (black) and simulated snowpack heights at NCO-P for the winter season 2004/05. The blue lines show results of simulations with the upgraded model including radiative transfer with constant BC concentrations of 100 ppb using the standard meteorological forcing data (full line) or forcing data with varying solid precipitation (see Table S1 for further information).

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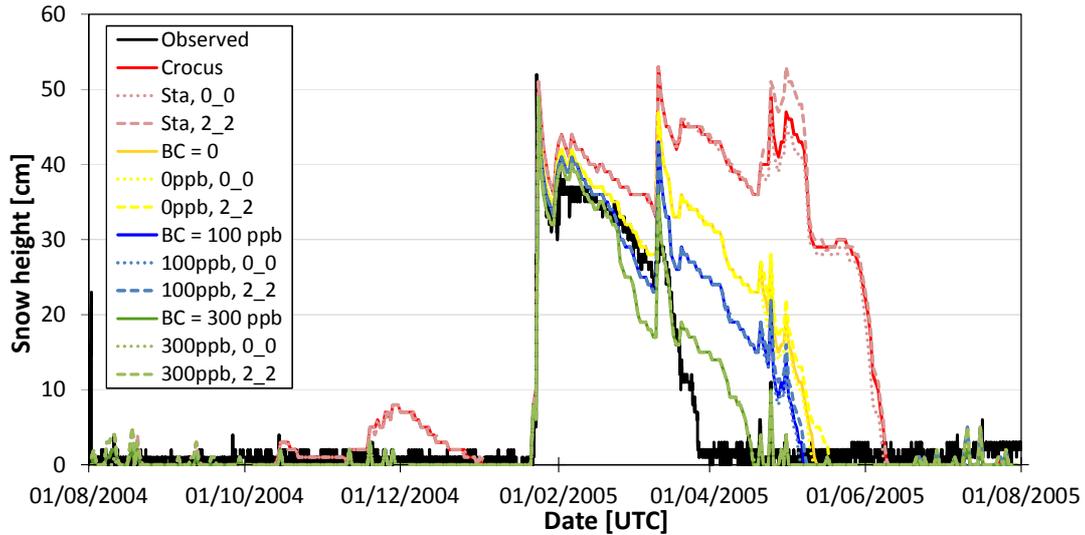
Figure S6. Comparison of observed (black) and simulated snowpack heights at NCO-P for the winter season 2004/05. Full lines show results of simulation with the standard meteorological forcing data and were performed with the standard crocus model (red) and with the upgraded model including radiative transfer with constant BC concentrations of 0 (yellow), 100 (blue), and 300 ppb (green). Results of the sensitivity runs "0_0" and "2_2" (see Table S1) are shown by dotted and dashed lines. Results of further sensitivity runs are within the range of these two runs.

Table S1. Summary of threshold temperatures for solid, mixed-phase, and liquid precipitation used to generate meteorological forcing data for the snow simulations. At air temperatures below the values in the column "Solid phase" all precipitations are assumed to be solid, at temperatures above the values in the column "Liquid phase" all precipitations are assumed to be liquid. "Mixed phase" gives the range with assumed 50 % solid and 50% liquid precipitation. Also given are the estimated totals for the solid precipitation. The total annual precipitation for 2004/05 was 491.7 mm. The "Standard" model run correspond to the meteorological forcing data used for all further simulations presented in the manuscript.

Model run	Solid phase	Mixed phase	Liquid phase	Solid precipitation
Standard	0 °C	0 – 2 °C	2 °C	204.0 mm
0_0	0 °C		0 °C	145.4 mm
0_1	0 °C	0 – 1 °C	1 °C	166.1 mm
1_2	1 °C	1 – 2 °C	2 °C	231.5 mm
2_2	2 °C		2 °C	275.4 mm
0_4	0 °C	0 – 4 °C	4 °C	277.6 mm

Table S2. Summary of statistical parameters for the comparison of observed and simulated albedo including bias (simulated – observed), root mean squared errors (RMSE) (simulated – observed), and correlation coefficients for linear regressions of simulated versus observed albedos. All values are calculated for the indicated periods of the winter snowpack for 2004/05, 2005/06, and 2006/07 and for the first month of each period. Averages of all parameters are calculated for the three winter seasons and for the first month periods.

Albedo	Bias (simulated – observed)				RMSE (simulated – observed)				Correl. Coeff. (simulated vs. observed)			
	Sta	BC = 0	BC = 100 ppb	BC = 300 ppb	Sta	BC = 0	BC = 100 ppb	BC = 300 ppb	Sta	BC = 0	BC = 100 ppb	BC = 300 ppb
2004/05												
22/01-01/04	0.292	0.223	0.196	0.163	0.295	0.237	0.218	0.198	0.089	0.272	0.337	0.429
22/01-21/02	0.119	0.051	0.027	-0.003	0.123	0.079	0.068	0.063	0.449	0.283	0.361	0.408
2005/06												
10/03-01/05	0.262	0.180	0.147	0.109	0.281	0.217	0.196	0.179	0.346	0.428	0.438	0.440
10/03-09/04	0.169	0.095	0.063	0.025	0.195	0.137	0.116	0.101	0.375	0.565	0.524	0.534
2006/07												
12/02-30/03	0.193	0.110	0.086	0.052	0.266	0.198	0.180	0.160	0.359	0.635	0.661	0.629
12/02-11/03	0.104	0.021	0.000	-0.034	0.185	0.120	0.106	0.091	0.504	0.536	0.597	0.604
Average												
Season	0.249	0.171	0.143	0.108	0.280	0.217	0.198	0.179	0.265	0.445	0.479	0.500
1. month	0.131	0.056	0.030	-0.004	0.168	0.112	0.097	0.085	0.443	0.461	0.494	0.515

Table S3. Summary of statistical parameters for the comparison of observed and simulated albedo including bias (simulated – observed), root mean squared errors (RMSE) (simulated – observed), and correlation coefficients for linear regressions of simulated versus observed albedos for the indicated different model runs using different meteorological forcing data: standard forcing used throughout the manuscript and the sensitivity runs"0_0" and "2_2" (see Table S1). All values are calculated for the indicated periods of the winter snowpack for 2004/05.

Albedo 2004/05	Sta	Sta, 0_0	Sta, 2_2	BC = 0	BC=0, 0_0	BC=0, 2_2	BC = 100 ppb	BC=100, 0_0	BC=100, 2_2	BC = 300 ppb	BC=300, 0_0	BC=300, 2_2
Bias (simulated – observed)												
22/01-01/04	0.292	0.291	0.292	0.223	0.223	0.223	0.196	0.196	0.196	0.163	0.163	0.163
22/01-21/02	0.119	0.119	0.119	0.051	0.051	0.051	0.027	0.027	0.027	-0.003	-0.003	-0.003
RMSE (simulated – observed)												
22/01-01/04	0.295	0.294	0.295	0.237	0.237	0.237	0.218	0.218	0.218	0.198	0.198	0.198
22/01-21/02	0.123	0.123	0.123	0.079	0.079	0.079	0.068	0.068	0.068	0.063	0.063	0.063
Correl. Coeff. (simulated vs. observed)												
22/01-01/04	0.089	0.107	0.086	0.272	0.269	0.275	0.337	0.339	0.346	0.429	0.425	0.429
22/01-21/02	0.449	0.449	0.449	0.283	0.283	0.283	0.361	0.361	0.361	0.408	0.408	0.408