Supplement of: “Albedo reduction of ice caused by dust and black carbon accumulation: a model applied to the K-transect, West Greenland”

T. Goelles and C. E. Bøggild

Correspondence to: T. Goelles (thomas.goelles@gmail.com)

Process	Potential albedo change	Sub-process	Values	Reference
Snow impurities		BC dust	−0.04 −0.019	with 20 cm^{2}g^{-1} and 0.02 ppm BC with 20 cm^{2}g^{-1} and 1. ppm dust
Snow other		SSA: ageing zenith angle clouds	−0.214 0.12 0.123	difference between 1600 and 20 cm^{2}g^{-1} $\hat{\alpha}_{S,*}$ of 0.65, no BC and a zenith angle of 89.9° $\hat{\alpha}_{S,*}$ of 0.65, no BC with cloud optical depth of τ=20
Ice impurities		BC dust	−0.213 −0.156	with 1.6 cm^{2}g^{-1} and 0.1 ppm BC with 1.6 cm^{2}g^{-1} and 9. ppm dust
Ice other		SSA: cracks ... zenith angle clouds	0.095 0.132 0.144	difference between 7 to 1.6 cm^{2}g^{-1} with 1.6 cm^{2}g^{-1} and 89.9° and no impurities with 1.6 cm^{2}g^{-1}, no BC with cloud optical depth of τ=20

FIGURE S1. Potential albedo changes in the ablation zone of the Greenland ice sheet, derived from the parameterisation of Gardner and Sharp, 2010. Dust and BC have the potential to lower the albedo of snow up to about 0.06, with high impurity loadings and very dense snow. Snow ageing has the potentially biggest influence on the albedo of snow and has to potential effect of up to o 0.21. Impurities on ice could lower the albedo by up to 0.37 in total. This is caused by the low specific surface area of ice and the high impurity concentrations caused by accumulation over several years. The zenith angle and the effects of clouds have the potential to alter the albedo of both snow and ice by more than 0.1.

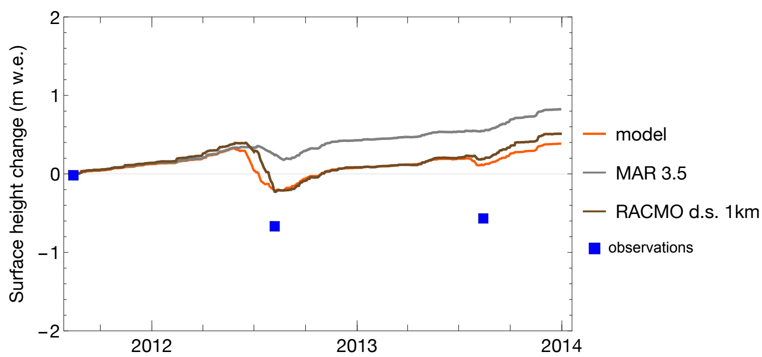

FIGURE S2. Surface height change at station KAN_U, starting at the first observation (Machguth and others, 2016) as reference.

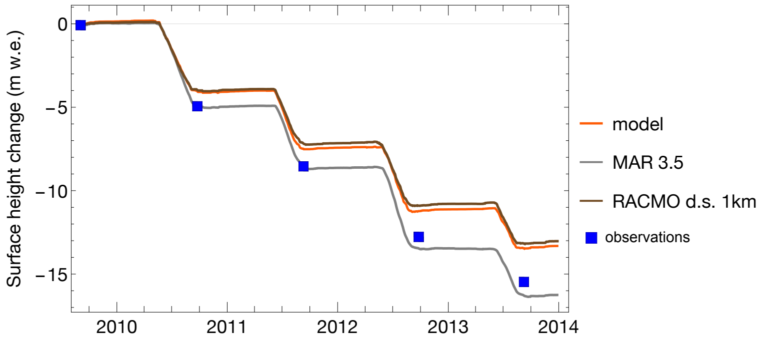

FIGURE S3. Surface height change at station KAN_L, starting at the first observation (Machguth and others, 2016) as reference.

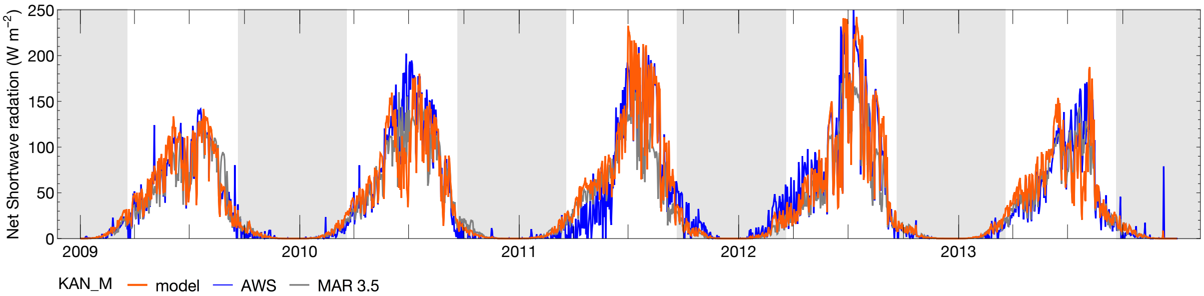

FIGURE S4. Comparison of net shortwave radiation at the station KAN_M during the period 2009-2014. The model simulation is compared to AWS data and the regional climate model MAR (Fettweis and others, 2016)

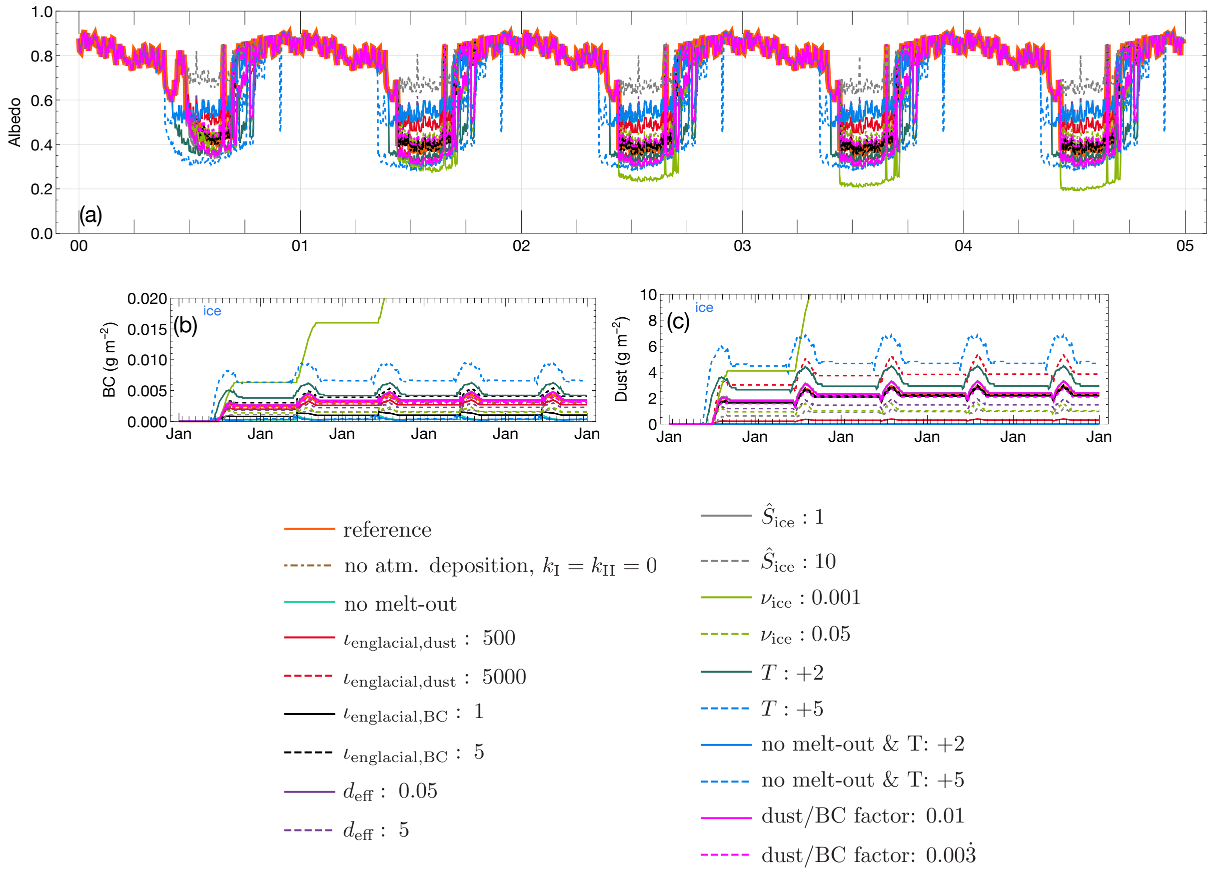

Figure S5. Sensitivity plots of (a) albedo, (b) the BC surface concentration on ice and (c) the dust surface concentration on ice. The settings are explained in the main text and these plots correspond to Figure 9.

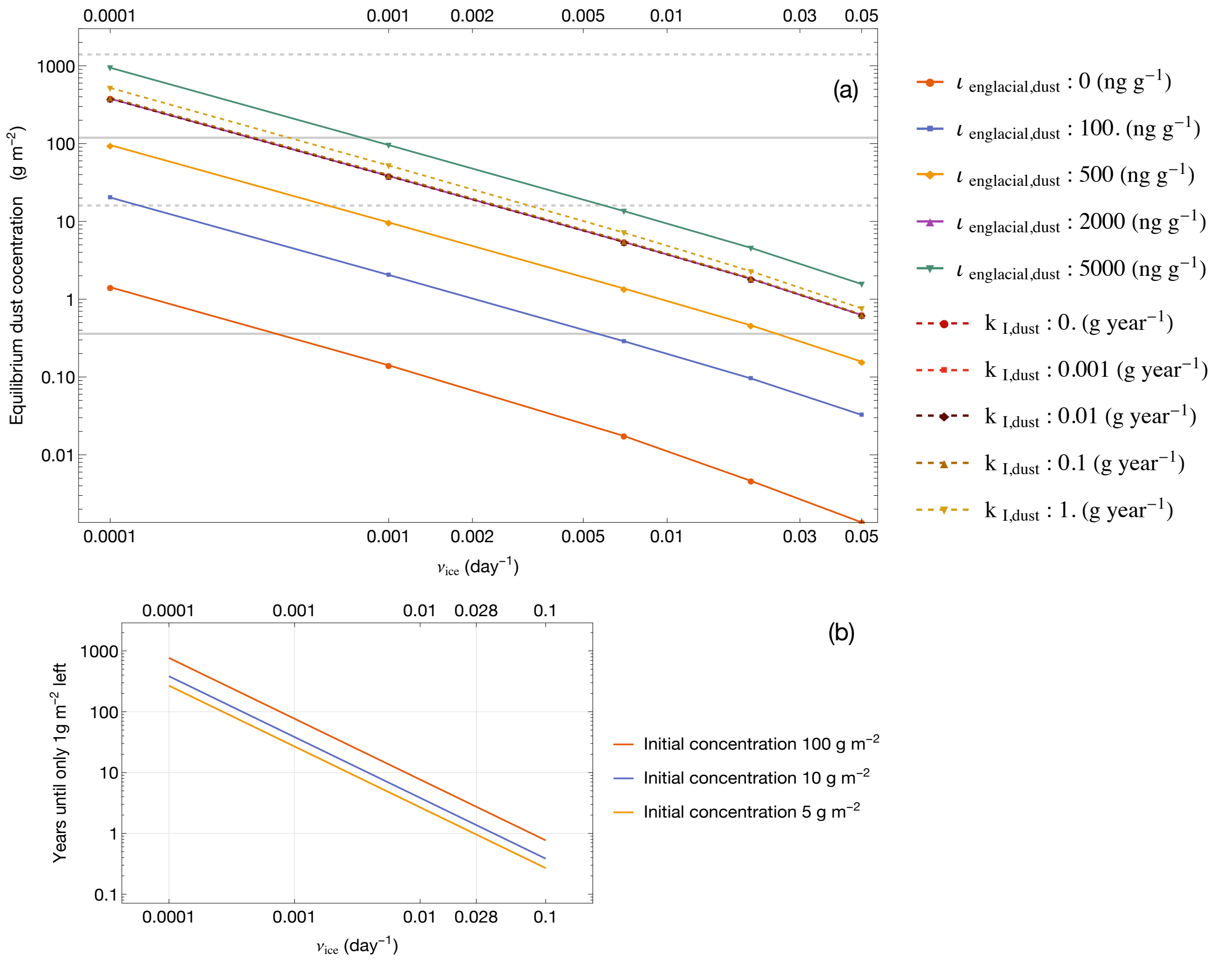

FIGURE S6. The effect of the reduction fraction on equilibrium surface concentrations of dust (a) and the esidence time of impurities (b). Panel (a) shows equilibrium surface concentrations of ice with different englacial concentrations and rates of atmospheric deposition in a log-log plot. The grey grid lines are observed surface concentrations of total impurity mass in Greenland for comparison. Full grey lines show the range of surface concentration from Takeuchi and others, 2014 of 0.36 to 119 g m^{-2} and dashed lines from Bøggild and others, 2010 of 16 to 1400 g m^{-2}. The boundary conditions are of KAN_M in 2010 with albedo from the AWS and a SMB of -2.08 m w.e.. The simulation is run until an equilibrium of atmospheric deposition, melt-out and impurity runoff is reached. The rates of atmospheric deposition ($k_{\mathrm{I,dust}}$) are varied while the englacial concentration is kept constant at 2000 ng g^{-1}. Only a 100 times larger atmospheric input rate of 1 g per square-meter and year gives a significantly higher equilibrium surface concentration. Panel (b) shows the time it takes to reach a surface concentration below 1 g m^{-2}, depending on the initial surface concentration and the reduction fraction by assuming 60 days of ice exposure each year and no additional input.

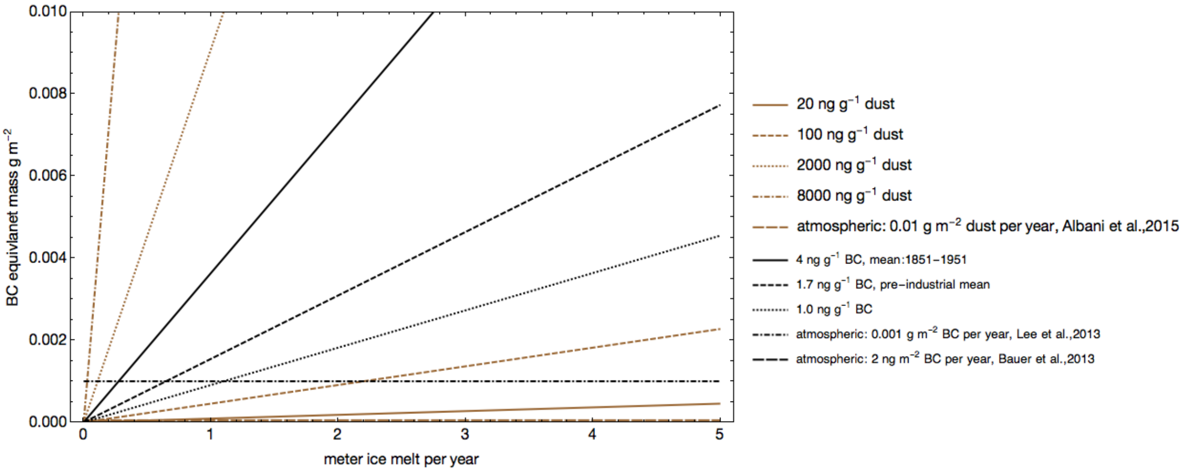

FIGURE S7. Comparison of annual melt-out and atmospheric deposition of BC (black) and dust (brown). The values of dust are converted in BC by assuming a 200 times weaker absorption. The atmospheric rate of deposition of dust is too low to be visible, therefore melt-out of dust is always the dominant source. The atmospheric deposition of BC is the dominant source when the englacial concentration is 1.0 ng g^{-1} and the annual melt below one meters. Otherwise, BC deposition is dominated by melt-out but atmospheric deposition still plays a significant role. This graph can also be used to guess which impurity is mostly responsible for lowering the ice albedo. If the concentrations of BC and dust are known then the steepest line belongs to the main contributor. For example, at KAN_L the BC concentration is 1.0 ng g^{-1} and the dust concentration 200 ng g^{-1}. The line of the BC concentration is steeper and therefore KAN_L is dominated by BC, which was also the result from the detailed simulation.

References

Bøggild CE, Brandt RE, Brown KJ and Warren SG (2010) The ablation zone in northeast Greenland: ice types, albedos and impurities. J. Glaciol., 56(195), 101–113 (doi: 10.3189/002214310791190776)

Fettweis X, Box JE, Agosta C, Amory C, Kittel C, Lang C, van As D, Machguth H and Gallée H (2017) Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. Cryosphere, 11(2), 1015–1033 (doi: 10.5194/tc-11-1015-2017)

Gardner A and Sharp M (2010) A review of snow and ice albedo and the development of a new physically based broadband albedo parameterization. J. Geophys. Res., 115(F1), F01009 (doi: 10.1029/2009JF001444)

Machguth H, Thomsen HH, Weidick A, Ahlstrom AP, Abermann J, Andersen ML, Andersen SB, Bjørk AA, Box JE, Braithwaite RJ, Bøggild CE, Citterio M, Clement P, Colgan W, Fausto RS, Gleie K, Gubler S, Hasholt B, Hynek B, Knudsen NT, Larsen SH, Mernild SH, Oerlemans J, Oerter H, Olesen OB, Smeets PCJP, Steffen K, Stober M, Sugiyama S, van As D, van den Broeke MR and Van de Wal RSW (2016) Greenland surface mass-balance observations from the ice-sheet ablation area and local glaciers. J. Glaciol., 62(235), 861–887 (doi: 10.1017/jog.2016.75)

Takeuchi N, Nagatsuka N, Uetake J and Shimada R (2014) Spatial variations in impurities (cryoconite) on glaciers in northwest Greenland. Bull. Glaciol. Res., 32(0), 85–94 (doi: 10.5331/bgr.32.85)