

Dear Referee,

Thank you very much for reviewing our manuscript.

Please see the revised manuscript for detailed change at the end of this document.

### **General comment:**

In the discussion paper the units of the specific surface area of ice (SSA) of  $\text{m}^2/\text{kg}$  was used instead of  $\text{cm}^2/\text{g}$ . The parameterisation of Gardner and Sharp uses  $\text{cm}^2/\text{g}$  and as a consequence Figures 5,6,7 have been redone.

The whole Monte Carlo process has been repeated and therefore the parameters in Figure 6c changed. The range of SSA goes now from 0.5 to 10  $\text{cm}^2/\text{g}$ , which corresponds to a SSA of ice with a density of  $880 \text{ kg/m}^3$  and above (Dadic et al., 2013).

As a consequence the mass of dust and BC on the ice surface have been changed in the text. We also mention the unit of SSA explicitly to avoid confusion.

### **Response to the comments:**

Referee comments are repeated in red.

1.)

“It is unclear to me what the added value of this model is to more sophisticated models like SNICAR that are also (reasonably) computationally efficient, and that anyway provide most of the parameterizations that are used in this model and that can be simplified as desired. “

SNICAR is developed for snow, while our model is suitable for ice and snow. In this study we focus on the description the model for one specific location over several annual cycles which includes dry/wet snow albedo and the albedo of ice. Hence, the difference is that our model consists of a framework which includes, besides snow albedo, the accumulation of aerosols and its influence on ice albedo. This can be seen in Figure 3 where in principle SNICAR could be used as the snow albedo part (row 4 in Figure 3), if all the required inputs are available. In this study the snow albedo is unaffected by BC and dust and consists of a predefined value for dry and wet snow (see 2.4.3).

To conclude:

- .) framework to model the annual albedo cycle of snow and ice surfaces, based on Robinson et al. (2010, 2011)
- .) calculation of melt-out of BC and dust
- .) surface accumulation of aerosols on ice
- .) bulk aerosol accumulation in the snow pack
- .) calculation of - ice - albedo reduction due to dust and BC

### **Major comments**

a) “The main weakness of the paper is that the active fraction (called ‘a very powerful parameter’ on page 1365) is used as a tuning parameter. This makes it possible to obtain almost any albedo reduction for any given dust concentration.

The reason for the active fraction being tuned is because we simply do not yet have enough published in situ results to have a robust parameterisation. Moreover, this parameterisation is not straight forward since Bøggild et al (2010) document an inverse relation between albedo and active fraction, so that with higher active fraction the albedo rises.

Good correlation has been obtained between the fraction of surface coverage of aerosols and resulting melting ice albedo. But a similar correlation between albedo and aerosol mass can not be obtained due to the complex interaction of processes behind. Melt down into cryoconite holes as well as flocculation by biological activity and hydrological transport all lead to a highly complex distribution of the aerosols on the melting ice surface. Therefore a “possible physical model for the active fraction” can at the present stage not be derived.

b) “As a result, the model is not universally applicable, as it must be calibrated for each location and year.”

The model formulation itself is universally applicable, but currently it requires calibration due to the lack of in situ observation constraining the parameterisation. As these observations become available and the physical relationships are better understood, the amount of free parameters will be reduced. Nevertheless, the basic framework will remain and if need be other darkening species can be added (Figure 3).

The model does not need to be calibrated for each year, as can be seen in Figure 6. The model is calibrated with data from one specific year and afterwards the calibrated model is applied for the rest of the period. For example when the model is calibrated with the data of 2010 the model also works well for 2011, 2012.

c) Another weakness is that concentrations of englacial dust, the main source of dust in the ablation zone, must also be prescribed.

That's only the case for this study and a solution to this is mentioned in the conclusions:

“Together with a transport scheme of englacial aerosols ...“

The follow-up study Goelles et al. (2015) includes ice dynamics and a transport scheme of englacial dust and BC.

d) “These deficiencies must be discussed and possible solutions provided, including a possible physical model for the active fraction.”

please see comment a) above and the paragraph starting at line 21 on page 1365. This paragraph has been extended.

e) Another serious flaw is the absence of an independent model evaluation using data different from those that were used to calibrate the model”.

See also comment to b) above. The model is calibrated for one year and then applied to the other years (Figure 6).

These can be extended in the future when more data is available.

### **Concluding remarks to the major comments**

In our opinion the strength of this paper is that it attempts to quantify the effect of aerosols on albedo and hence melt. This relation is obvious from just observing the amount of dust on melting glacier ice. But, despite this we are not aware of earlier publications attempting to quantify the relation between mass, active fraction and albedo. To us this indicates the complex surface processes of melting glacier ice leading to the albedo. The manuscript here sheds light on the importance of aerosols on melt despite not having a robust relation between mass of active fraction and albedo available yet.

## Minor comments

p. 1361: "The high ice albedos at S5 makes it necessary to set the active fraction of BC and dust to zero." Setting the active fraction to zero means that the simulated concentrations are no longer important. But does this not simply reduce the model to an interpolation between snow and ice albedo?

That's true for the station S5 in the year 2011, where the ice albedo is not influenced by BC and dust. There the surface albedo scheme is basically reduced to dry/wet snow albedo and ice albedo defined by the specific surface area (SSA) of ice. Nevertheless that's not the case for KAN\_M and other stations.

p. 1349: the distinction between 'atmosphere' and 'tundra' is not mutually exclusive: dust from the tundra also reaches the ice through the atmosphere. Better: atmosphere (from distant sources) and atmosphere (from local sources).

Yes that's true and is changed accordingly throughout the text.

p. 1350: it is assumed that once incorporated in the snowpack, particles will not be suspended again into the atmosphere. But what if drifting snow sublimates into the air, releasing particles that were originally included? Could this be a significant effect?

According to Box and Steffen (2001) the Greenland ice sheet has a 12% or 23% precipitation loss from sublimation. The sublimation in the ablation zone is less since surface melt presents solid to gas sublimation for several months. Therefore, and because of higher precipitation we estimate that the effect is a few % at the most.

Section 4.2: the model fails to reproduce the 2009 high mid-summer albedo: "... year 2009 was problematic as the autumn snow cover was building up earlier than normal." But isn't a model specifically meant to reproduce non-normal events? This requires more reflection and discussion.

We changed to last paragraph in Section 4.2 and added more discussion in Section 5.3 which is dealing with the year 2009 at the KAN\_M station.

p. 1365, l. 14: 'validated' is not the right word here for two reasons. First, models can only be evaluated, not validated, because by definition they are an approximation of reality. Secondly, the albedo model was calibrated using the same data, so there is no independent evaluation. Perhaps the phrase 'applied to' or 'tested with' is better to use here.

We changed the phrase to "tested with".

p. 1348, l. 13: The SNICAR model is already implemented in various large scale models, and is not too computationally demanding for long term applications.

Ultimately it's a question of how powerful the machine is and how much time a simulation can take. A longer term application would need 1 day time-step for several 100k years and in addition all the required input data needs to be provided. We deleted this sentence.

## Textual comments

Thanks for the comments. Everything was changed accordingly in the revised version. Here are some clarifications

p. 1354, l. 9: 'At high zenith angles close to solstice at Kangerlussuaq the maximum albedo increase with high impurity loadings is below 0.04' Please provide reference for this statement.

Own calculation with the equations by Gardner and Sharp 2010 with zenith angles up to 50°. We rewrote the sentence.

Figure 6, caption: " The parameters are optimised for different yeas and then used to simulate the entire period" What is meant here? What parameter values are ultimately chosen?

What is meant here is that for example the orange line with the label "2009" used 2009 data to calibrate the model and afterwards the calibrated model is used to simulate the whole period 2009-2012. This means that the model is "trained" with data from 2009 and tested on the rest of the period, without recalibration. Please see also the reply to the major comments. The caption is now rewritten with the aim to make this more clear.

Sincerely,  
T. Goelles and C. E. Bøggild

## References

Box, J. E. and Steffen, K.: Sublimation on the Greenland Ice Sheet from automated weather station observations, *Journal of Geophysical Research: Atmospheres* (1984–2012), 106(D24), 33965–33981, doi:10.1029/2001JD900219, 2001.

Dadic, R., Mullen, P. C., Schneebeli, M., Brandt, R. and Warren, S. G.: Effects of bubbles, cracks, and volcanic tephra on the spectral albedo of bare ice near the Transantarctic Mountains: Implications for sea glaciers on Snowball Earth, *J Geophys Res-Earth*, 118(3), 1658–1676, doi: 10.1002/jgrf.20098, 2013.

Goelles, T., Bøggild, C. E. and Greve, R.: Ice sheet mass loss caused by dust and black carbon accumulation, *The Cryosphere Discuss.*, 9(2), 2563–2596, doi:10.5194/tcd-9-2563-2015, 2015.

Bøggild, C. E., Brandt, R., Brown, K. and Warren, S. G.: The ablation zone in northeast Greenland: ice types, albedos and impurities, *Journal of Glaciology*, 56(195), 101–113, doi: 10.3189/002214310791190776, 2010.

Robinson, A., Calov, R. and Ganopolski, A.: An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change, *The Cryosphere*, 4(2), 129–144, doi:10.5194/tc-4-129-2010, 2010.

Robinson, A., Calov, R. and Ganopolski, A.: Greenland ice sheet model parameters constrained using simulations of the Eemian Interglacial, *Clim Past*, 7(2), 381–396, doi:10.5194/cp-7-381-2011, 2011.

Manuscript prepared for The Cryosphere Discuss.  
with version 2014/07/29 7.12 Copernicus papers of the  $\LaTeX$  class copernicus.cls.  
Date: 14 May 2015

# Albedo reduction caused by black carbon and dust accumulation: a **quantitative** quantitative model applied to the western margin of the Greenland ice sheet

T. Goelles<sup>1,2</sup> and C. E. Bøggild<sup>3</sup>

<sup>1</sup>The University Centre in Svalbard (UNIS), Longyearbyen, Norway

<sup>2</sup>Norwegian University of Life Sciences (NMBU), Aas, Norway

<sup>3</sup>Arctic Technology Centre, Technical University of Denmark, Kgs. Lyngby, Denmark

Correspondence to: T. Goelles (thomas.golles@unis.no, thomas.goelles@gmail.com)

## Abstract

Ice loss due to surface melt of the Greenland ice sheet has increased in recent years. Surface melt in the ablation zone is controlled by atmospheric temperature and surface albedo. Impurities such as mineral dust and black carbon darken the snow and ice surfaces and therefore reduce the surface albedo ~~which~~. This leads to more absorbed solar energy ~~and ultimately amplifying~~ which ultimately amplifies melt. These impurities accumulate on the ice surface both from atmospheric fallout and by melt-out of material which was enclosed in the snowpack or the ice compound. A general impurity accumulation model is developed and applied to calculate the surface albedo evolution at two locations in western Greenland. The model is forced either by regional climate model output or by a parameterisation for temperature and precipitation. Simulations identify mineral dust as the main contributor to impurity mass on ice, where the dominating part originates from melt out of englacial dust. Daily reduction of impurities is in the range of one per-mille which leads to a residence time of decades on the ice surface. Therefore, the impurities have a prolonged effect on surface melt once they are located on the ice surface. The currently englacially stored mineral dust and black carbon will effect future melt and sea level rise and can be studied with the presented model.

## 1 Introduction

Sea level rise due to melting and calving of ice sheets and glaciers is a major concern in association with climate change and has attracted considerable attention. Ice loss of the Greenland Ice Sheet (GrIS) has increased in recent years (Vaughan et al., 2013) where until 2009 the ice loss due to surface melt accounted for 50 % (Van den Broeke et al., 2009a) and up to 84 % after (Enderlin et al., 2014).

Absorption of shortwave radiation is the largest energy source for ice and snow melt (i.e. Male and Granger, 1981; Cuffey and Paterson, 2010). Surface albedo and incident radiation are controlling the amount of absorbed shortwave radiation, hence surface albedo has

been identified as a major component of the surface mass balance for ice sheets (e.g. van Angelen et al., 2012; Bougamont et al., 2005; Tedesco et al., 2011). Despite the importance of albedo it is rarely included in ice sheet ~~model~~ models and if it is then it is usually treated as constant in time and space (e.g. Konzelmann and Braithwaite, 1995; Hock and Noetzli, 1997; Robinson et al., 2011, 2010; Bougamont et al., 2005). Sensitivity experiments of the GrIS (Machguth et al., 2013) suggest that the present high mass loss could be 20–30 % higher if the surface albedo would be significantly lower in the future. Currently a downward trend in the surface albedo is observed at the GrIS margin with a decrease by up to 18 % in coastal regions (Box et al., 2012).

Impurities such as black carbon (BC), mineral dust (Warren and Wiscombe, 1980) and microbes affect the albedo of snow and ice. Microbes may influence the albedo by aggregating material (Takeuchi et al., 2001) and by producing dark materials (Takeuchi, 2002; Remias et al., 2012). Yet the influence ~~of~~ of microbes on surface albedo remains to be quantified (Stibal et al., 2012; Yallop et al., 2012) as its dynamics are currently not well understood. Other impurities are aerosols, which in the context of glaciers, are eolian transported particles which are located on, or inside the snowpack and glacier ice. Only at the very margin surfacing till from the base of the glacier ~~become significant and can~~ can be significant and locally affect the albedo. Albedo relevant aerosols are BC originating from natural or man-made forest fires or incomplete fuel composition as well as mineral dust produced by weathering of the earth surface. Mineral dust (subsequently referred to as just dust) is the main contributor to total impurity mass (e.g. Takeuchi et al., 2014) but BC is much more effective in reducing albedo (Warren and Wiscombe, 1980). Just a few nanogram of BC have a significant impact on ice and snow albedo. Termination of the little ice age has been reported to be possibly caused by industrial BC (Painter et al., 2013).

Large ice masses act as a reservoir of dust and BC by entraining the particles in the accumulation zone which are later released at the margin after centuries or millennia of transport. These englacial impurities accumulate (e.g. Oerlemans, 1991; Bøggild et al., 1996; Klok and Oerlemans, 2002; Oerlemans et al., 2009) at the ice surface as they melt-out and therefore have a long-time effect on surface melt. Between 1850 ~~to~~ and 1951 North Amer-

ica ~~is~~ was probably the main source of BC in central Greenland where current emissions are almost back to pre-industrial levels (McConnell et al., 2007). Nevertheless today the main source is probably Asia (McConnell et al., 2007; Koch and Hansen, 2005) ~~also found to be~~ which was also the main source of dust in the past (Biscaye et al., 1997). Asian BC emissions were rising since 2000 and in particular in China by about 30 % (Lei et al., 2011) to 40 % (Lu et al., 2011).

Together with the high concentrations of dust from glacial times currently stored inside the GrIS this forms a potential major source of uncertainty to future sea level rise. Model projections of future melt of glaciers and ice sheets might be underestimated without accounting for the influence of impurities on ice albedo.

Sophisticated snow albedo models like SNICAR (Flanner and Zender, 2006) have existed for some time. ~~While these models are computationally to demanding to include in large scale models they give important insight to efficient parameterisations (Pirazzini, 2009).~~ Global circulation models use different snow albedo models with different levels of complexity and some ~~may include simple parameterisation of impurities~~ ~~(?)~~ include the effect of impurities on snow albedo (Dolan et al., 2015). However, a physical ~~based~~ model of ice albedo which includes the accumulation of impurities is still missing.

Our goal in this paper is twofold. Firstly, development of a computationally efficient albedo model which takes outcropping and accumulation of impurities on the ice surface into account. Secondly, we examined the relative contribution of outcropping dust and BC to the total impurity mass and investigate its residence time on the surface at two locations on the western margin of Greenland based on local meteorological data.

## 2 Model description

### 2.1 Impurity accumulation

The surface albedo of an ice sheet (Fig. 1) is influenced by several processes. In principle there are three factors: optical properties of the surface (albedo), angle of incidence

of downward radiation and proportions of direct to diffuse radiation (Cuffey and Paterson, 2010).

The surface property of an ice sheet is primarily **effected** **affected** by surface type (snow or ice) and secondarily by the optical surface properties. This is because the difference between snow and ice albedo is normally greater than between dry and wet snow. The optical properties of snow and ice are determined by impurities and the specific surface area of the material. The specific surface area of snow is determined by snow metamorphism and of ice by enclosed air, cracks and the magnitude of the ablation crust (Müller and Keeler, 1969). The magnitude of diffuse scatter below the surface and therefore the albedo is **effected** **affected** by this specific surface area.

Impurities such as BC, mineral dust and microbes have different origins **and** **before** accumulating on the ice and snow surface. There are four different sources of impurities at the ice surface in the ablation zone (Fig. 2):

- *atmosphere: distant sources*:  $k_I$  by dry or wet deposition,
- *tundra atmosphere: local sources*:  $k_{II}$  by regionally transported material from the surrounding tundra,
- *flow*:  $k_{III}$  by transport from the accumulation zone to the ablation zone where impurities melt-out,
- *local*:  $k_{IV}$  by local biological production of dark material on the ice or snow surface.

For model purpose the accumulation has to be treated separately for each impurity species with different considerations for snow and ice. Since the microbiological interaction is not yet well understood we limit ourself to BC ( $n = 1$ ) and dust ( $n = 2$ ) only in this study. Nevertheless the equations can be applied for other species, including microbes. We treat the impurities  $\iota$  as a mass per area ( $\text{ng m}^{-2}$ ). If snow melts then all the impurities are deposited on the ice surface and all the sources contribute directly to the amount on the ice surface. On the other hand if snow covers the ice surface ( $d > 0$ ) all the sources contribute to the amount in the snowpack and the impurities amount on the ice surface remains

constant. Hence the impurity amount located on top of the ice is preserved from one melt season to the next with the additional influx of material from the melted winter snowpack. The total amount is balanced by reduction ( $r_{ice,n}(t)$ ) from the ice surface due to meltwater removal and we assume no loss of impurities up into the snowpack. Moreover, resuspension of formerly deposited aerosols is not likely due to the fact that the surface is either wet or refrozen with the impurity entrained in the frozen ice. We also assume that once aerosol is in the snowpack it is not resuspended again.

Impurity accumulation inside the snowpack (Eq. 1) and on the ice surface (Eq. 2) are described in general by:

$$\frac{d\iota_{snow,n}}{dt} = \begin{cases} k_{I,n}(t) + k_{II,n}(t) + k_{IV,n}(t) & d > 0 \\ 0 & d = 0 \end{cases} \quad (1)$$

$$\frac{d\iota_{ice,n}}{dt} = \begin{cases} 0 & d > 0 \\ k_{I,n}(t) + k_{II,n}(t) + k_{III,n}(t) + \\ + k_{IV,n}(t) - r_{ice,n}(t) & d = 0 \end{cases} \quad (2)$$

The in situ production term  $k_{IV,n}(t)$  is only relevant for microbiological activity and is zero otherwise.

~~When ice is melting the impurities~~ Impurities which have been transported with the ice from the accumulation zone resurface ~~as they melt out and therefore contribute tot and contribute to~~ the impurity mass at on the ice surface. This is described by the term  $k_{III,n}(t)$  in Eq. (2). We assume that superimposed ice ( $h_{s,ice}$ ) does not contain any impurities since impurities will not be transported downward with melt water during snow melt, but instead accumulate on the snow surface. Otherwise the source of impurities depends on the englacial impurity concentration nearest to the ice surface, the amount of melt and ice density:

$$k_{III,n}(t) = \begin{cases} [l_{n,englacial}] \Delta h_{ice} \Delta t_b^{-1} \rho_{ice} & h_{s,ice} = 0 \\ 0 & h_{s,ice} > 0 \end{cases} \quad (3)$$

For a sufficient short time steps in Eq. (3) ( $\Delta t_b$ ) ice melt  $\Delta h_{\text{ice}}$  is small enough **that and** the englacial aerosol concentration ( $[L_{n,\text{englacial}}]$ ) can be treated as constant. In this study we prescribe the englacial  $[L_{n,\text{englacial}}]$  concentration with values from shallow ice cores.

## 2.2 Surface mass balance

It is necessary to compute ice melt and **the** snow thickness ( $d$ ) for the accumulation equations and later also for the resulting surface albedo. The daily change of snow pack height  $d$  and ice thickness  $h_i$  for the melt-out of englacial impurities with Eqs. (4) and (5) (Robinson, 2011) reads:

$$\frac{d}{dt_b}d = P_{\text{solid}} - M_s, d \in (0, d_{\text{max}}) \quad (4)$$

$$\frac{d}{dt_b}h_i = \begin{cases} M_s r_f & d > 0 \\ \min(P_{\text{solid}} - M_s, 0) & d = 0 \end{cases} \quad (5)$$

where  $P_{\text{solid}}$  is the solid precipitation and  $M_s$  the potential melt rate which will be described in the next section in more detail.

If the snow depth exceeds  $d_{\text{max}} = 5$  m (consistent with Robinson et al., 2010; Fitzgerald et al., 2012) the excess amount is added to the ice thickness and the snow thickness is reset to 5 m.

The amount of solid precipitation rate  $P_{\text{solid}}$  in Eq. (5) depends on a temperature dependent fraction  $f(T)$  and the total amount of precipitation  $P$ :

$$P_{\text{solid}} = P \cdot f(T) \quad (6)$$

The surface temperature depending fraction  $f(T)$  is empirically based on data of Greenland (Bales et al., 2009; Calanca et al., 2000) and states that below a minimum temperature

$T_{\min}$  ( $-7^{\circ}\text{C}$ ) all precipitation is snow and above a maximum temperature ( $+7^{\circ}\text{C}$ ) rain:

$$f(T) = \begin{cases} 1 & T < T_{\min} \\ 0 & T > T_{\max} \\ \cos\left(\frac{T-T_{\min}}{T_{\max}-T_{\min}}\right)\left(\frac{\pi}{2}\right) & T_{\min} < T < T_{\max} \end{cases} \quad (7)$$

Refreezing within a snowpack is a function of the snow depth and the surface temperature  $T$ :

$$rf = \begin{cases} 0 & d = 0 \\ r_{\max}f(T) & 0 < d \leq 1 \\ r_{\max} + [(1 - r_{\max})(d - 1)] & 1 < d \leq 2 \\ 1 & d > 2 \end{cases} \quad (8)$$

In the absence of snow the refreezing fraction is 0. Between 0 and 1 m w.e. the refreezing fraction is following the definition in Janssens and Huybrechts (2000) and also depending on  $f(T)$ . Where  $r_{\max}$  is the fraction of melt precipitation that has to ~~that has to~~ refreeze before runoff can occur (Fitzgerald et al., 2012).

### 2.3 Melt

We use a simplified energy-balance model based on Oerlemans (2001) and recently applied ~~for to~~ Greenland (Robinson et al., 2010, 2011; Fitzgerald et al., 2012):

$$M_s = \frac{1}{\rho_w L_m} [\tau_a(1 - \alpha_s)S_{\text{TOA}} + c + \lambda T] \quad (9)$$

Where  $\rho_w$  is the density of water,  $L_m$  is the latent heat of melting,  $\tau_a$  is the transmissivity,  $S_{\text{TOA}}$  the insolation on top of the atmosphere,  $c$  and  $\lambda$  are empirical parameters for short-wave radiation and sensible heat flux and long-wave radiation respectively and  $T$  is the

surface air temperature. Equation (9) requires only the information of the insolation on top of the atmosphere which can be calculated for any time by simple equations (Liou, 2002). The transmissivity  $\tau_a$  is based on summer (April–September) radiation data over Greenland and is a linear fit with elevation  $h$  in meters (Robinson et al., 2010):

$$\tau_a = 0.46 + 0.00006 h \quad (10)$$

The only variable which remains to be described in Eq. (9) is the surface albedo.

## 2.4 Surface albedo

### 2.4.1 General albedo ~~paramterisation~~parameterisation

In the absence of snow the surface albedo in Eq. (9) is identical to the ice albedo (see also Fig. 1). From bare ice to a critical snow depth  $d_{\text{crit}}$  the surface albedo fades linearly to the snow albedo:

$$\alpha_s = \begin{cases} \alpha_{\text{ice}} & d = 0 \\ \alpha_{\text{ice}} + \frac{d}{d_{\text{crit}}} (\alpha_{\text{snow}} - \alpha_{\text{ice}}) & 0 < d < d_{\text{crit}} \\ \alpha_{\text{snow}} & d \geq d_{\text{crit}} \end{cases} \quad (11)$$

Even with a few centimetres of snow bare ice can be exposed due to meter scale surface undulations of the glacier ice surface and the effect of wind drift.

Equation (11) is a more generalised version of the one used in Robinson et al. (2010, 2011) which uses the parameterisation of Van den Berg et al. (2008). This parameterisation allows the snow albedo to be lower than the ice albedo.

The basic method for snow and ice albedo are the same where the albedo is composed of the base albedo and the sum of albedo reductions due to impurities and the influence of the solar zenith angle  $d\alpha_{\theta_z}$ :

$$\alpha_{\text{ice|snow}} = \alpha_{\text{base}} + \sum_1^n d\alpha_{\iota, n} + d\alpha_{\theta_z} \quad (12)$$

The influence of clouds on albedo is already included in the melt scheme and optimised for GrIS (Robinson et al., 2010) via Eq. (10). The albedo change due to ~~sun zenith angle~~ the zenith angle of the sun is also parameterised with the scheme of Gardner and Sharp (2010). ~~At high zenith angles~~ With high impurity loadings and high zenith angles, close to solstice at Kangerlussuaq ~~the~~, the equations results in a maximum albedo increase ~~with high impurity loadings is below~~ of less than 0.04. Therefore, we neglect the influence of solar angle for the moment as our main focus is on ice albedo.

## 2.4.2 Ice albedo

The base albedo of ice is computed via the specific surface area  $\hat{S}$  (in  $\text{cm}^2 \text{g}^{-1}$ ) with Eq. (13) (Gardner and Sharp, 2010):

$$\alpha_{\text{base}} = 1.48 - \hat{S}^{-0.07} \quad (13)$$

The albedo reduction due to BC is calculated with the parameterisation in Eq. (14) (Gardner and Sharp, 2010). Dust is included by adding a BC equivalent mass to the BC amount, ~~as dust is about 1/200 (Gardner and Sharp, 2010) less~~ with BC being about 200 times (Gardner and Sharp, 2010) more effective per mass:

$$d\alpha_{\ell,n} = \max \left( 0.04 - \alpha_{\text{base}}, \frac{-[\ell_{\text{eff},n}]^{0.55}}{0.16 + 0.6\hat{S}^{0.5} + 1.8[\ell_{\text{eff},n}]^{0.6}\hat{S}^{-0.25}} \right) \quad (14)$$

Where  $\ell_{\text{eff,BC}}$  is the effective aerosol concentration in ppm described as:

$$[\ell_{\text{eff},n}] = [\ell_{n,\text{englacial}}] + [\ell_{\text{ice},n}] \cdot \mathcal{F}_{\text{ice},n} \quad (15)$$

The *active fraction*  $\mathcal{F}_{\text{ice},n}$  describes the fact that not all impurities ~~are influencing the albedo~~ influence the albedo directly. Measurements of cryoconite holes at the GrIS margin (Bøggild et al., 2010) has shown that a considerable mass of impurities, in the order of kilograms per square meter, is located inside the cryoconite holes. The holes are vertical

but the incident solar radiation is mostly ~~non-zenith-reducing-not in zenith direction, which reduces~~ the impact of radiation on impurity melt ~~in-at~~ the bottom of the hole to nearly zero.

Since Eq. (14) requires a concentration in ppm and the accumulation model handles the total amount in  $\text{ng m}^{-2}$  a conversion is necessary:

$$[l_n] = \frac{l_n}{\rho d_{\text{eff}}} 10^6 \quad (16)$$

Where the impurity concentration is in ppm when the impurity amount is in  $\text{ng m}^{-2}$  and the effective depth  $d_{\text{eff}}$  is in meters and density is in  $\text{kg m}^{-3}$ . The effective depth and the active fraction on ice are not well constrained and both have the same effect on the results. They both describe how effective the total amount of aerosol is in reducing the albedo. This effective depth is related ~~on-to~~ the absorption length in ice ~~which is depending-, which depends~~ on wavelength and impurities. We set the effective depth to 5 m which corresponds to an extinction coefficient of about  $1 \text{ m}^{-1}$  which is in the range of totally clear and white ice (Male and Gray, 1981) and leave the active fraction as a free parameter.

### 2.4.3 Snow albedo

In this study we focus ~~manly-mainly~~ on ice albedo and therefore ~~left the snow albedo is defined by differentiating we only differentiate~~ between wet and dry snow ~~albedo~~ as in Robinson et al. (2010) ~~although-, even though~~ the model includes ~~also~~ snow albedo reduction due to BC and dust. This does not limit the main conclusions of this study as accumulation of BC and dust inside the snowpack is included. On a side note, our snowpack model has no layers but impurities such as BC (Doherty et al., 2013) are usually located close to the surface which can be accounted for with a high active fraction.

## 2.5 Model setup

Figure 3 shows the flow chart of the model for one time-step. First the climate parameters are updated and the ~~snow-depth-snow depth~~ is calculated with the melt amount from the previous time-step. Then the aerosol accumulation of BC and dust in snow and on the ice

surface is calculated which are ~~then~~ passed to the snow and ice albedo modules. Where different methods of ~~calculating the albedo~~ albedo calculation from aerosols are implemented and in this study the parameterisation from Gardner and Sharp (2010) is used. ~~Then the resulting surface type and albedo is derived and used as input to~~ The albedo and surface type is used to derive the potential melt ~~scheme, which affect the refreezing amount and ultimately in~~ which affects the amount of refreezing meltwater and ultimately the surface mass balance. Model components can be exchanged in future versions, where for example SNICAR could be used as the snow albedo component.

### 3 The model applied to the western margin of Greenland

#### 3.1 K-transect

The model is tested and forced with data from the K-transect (also known as Søndre Strømfjord transect) on the western Greenland margin near Kangerlussuaq airport (Fig. 4) at a latitude of 67° N. The transect is about 140 km long and ~~reach~~ reaches from an elevation of 460 up to 1850 m i.e. above the equilibrium line which is located around 1500 m (Van de Wal et al., 2005) and KAN\_U and S10 are located in the accumulation zone. The Institute for Marine and Atmospheric Research in Utrecht (IMAU) and later the Geological Survey of Denmark and Greenland (GEUS) (Van As et al., 2011) each operate three automatic weather stations (AWS). Even before IMAU installed the first AWS (S5, S6, S9) for continuous measurements since 2003 (Van den Broeke et al., 2009b) surface mass balance studies have been done (Van de Wal et al., 2012) since the beginning of the 1990s. A dark region persists below the equilibrium line (Van de Wal, 1992 as cited in Wientjes and Oerlemans, 2010) in each year. At 67° N the dark region is about 30 km wide and starts at approximately 30 km away from the margin (Wientjes and Oerlemans, 2010). Previously meltwater was believed to be the cause (Zuo and Oerlemans, 1996) but now is attributed to dust (Wientjes and Oerlemans, 2010) and carbonaceous particles (Wientjes et al., 2012).

Reference surface albedo is calculated from daily mean data from the GEUS stations and hourly data for IMAU stations, where only data with a solar angle above  $15^\circ$  are used. This was found to be in agreement with the data where as  $10^\circ$  was used (Van As et al., 2005) before.

### 3.2 Experimental design and parameters

In order to compute the impurity and albedo evolution at the K-Transect the model parameters needs to be adjusted specifically for this particular environment. Some standard physical parameters common for all locations are listed in Table 1.

The model is applied to stations KAN\_M and S5 because they both have the full cycle with dry snow, wet snow and exposed ice over the annual cycle. Station KAN\_M is situated in the dark zone at 1280 m a.s.l and S5 is close to the margin at 460 m a.s.l with more reflectant ice but higher surface ablation due to higher temperatures. Station S5 has the longer record and was chosen over KAN\_B and KAN\_L. Station S6 has only complete data for the period 2005–2007 and was therefore left out.

Adjustable free parameters are: dry snow albedo, wet snow albedo, critical snow depth, the active fraction of BC and dust on ice, the specific surface area of ice and reduction fraction on ice. Which makes in total six free parameters.

The best parameter combination was derived by a Monte-Carlo method [with 500 random realisations](#) by taking the combination with the lowest value of  $S$  after a spin-up:

$$S = \sum_{01.04}^{30.09} |\alpha_{\text{mod}} - \alpha_{\text{dat}}| \quad (17)$$

Parameter ranges taken into account can be seen in Fig. 6c. The [specific surface area of ice ranges from 0.5 to 10  \$\text{cm}^2 \text{g}^{-1}\$ , based on a density of 880  \$\text{kg m}^{-3}\$  and above \(Dadic et al., 2013\)](#). The active fraction of dust and BC was further optimised manually to improve the fit between model and observation after the Monte-Carlo search.

We use 100 years for the spin-up in order to guarantee that the model reaches an equilibrium with all parameter combinations. This long spin-up time also allowed to start with

no snow and without ~~aerosols on~~ accumulated aerosols on both snow and ice. In practice with realistic parameter combinations the equilibrium is reached much earlier and how long it takes is primarily controlled by the reduction fraction.

The englacial BC value from KAN\_M is taken from an ice core (Wientjes et al., 2012) at location S8 (7.25 km south-west) and is  $4 \text{ ng g}^{-1}$ . For S5 the value is set to  $1 \text{ ng g}^{-1}$  based on the closely located S1 core.

For dust the englacial value at KAN\_M is set to 2000 and  $100 \text{ ng g}^{-1}$  at S5 as it is located in a cleaner region. These values are based on assumptions from the NGRIP core (Ruth, 2007) and the effect of these assumptions is discussed later (Sect. 5.2).

The atmospheric input rate (~~k<sub>H</sub>~~ from distant sources ( $k_i$ )) of BC at both stations is  $20 \text{ ng m}^{-2} \text{ a}^{-1}$  (Bauer et al., 2013) which also corresponds to the maximum value found in a snow sample close to Dye-2 (Doherty et al., 2013). For dust a value of  $1 \text{ g m}^{-2} \text{ a}^{-1}$  taken everywhere from the mean value of Mahowald et al. (1999). The melt-out rate of aerosols is calculated (~~k<sub>H</sub>~~  $k_{ij}$ ) and all the other contributors from tundra ( $k_{ij}$ ) and local production ( $k_{ij}$ ) are assumed to be zero. This might lead ~~for to~~ an underestimation of ~~the dust~~ dust, as a significant amount could be transported from the surrounding tundra to the ice. Nevertheless ~~the tundra input~~, the atmospheric input from local sources ( $k_{ij}$ ) might be neglect-able as the dark region is 30 km away from the margin which indicates the insignificance of direct input from the tundra (Wientjes and Oerlemans, 2010).

The experiments are carried out once with temperature from AWS data and daily precipitation from MAR (Tedesco et al., 2014) model output and once with the parameterisation of those, as presented in the next section.

### 3.3 Temperature and precipitation parameterisation

As the model should be applicable ~~for studies with long timescale~~ long timescales, a parameterisation of temperature and precipitation is required. The temperature ~~in at~~ the K-transect has a high variability in the cold months (Figs. 5 and 7a) and is stably during the warmer summer season due to the fact that ice is ~~cooling~~ lowering air temperatures during melt. Therefore, we choose to parameterise the near surface air temperature not with a sinu-

soidal shape otherwise used (e.g. Reeh, 1991) but via a trapezoid shape:

$$T = \begin{cases} T_+ & t_{\text{O,start}} \leq t \leq t_{\text{O,end}} \\ t\zeta - t_{\text{O,start}}\zeta + T_+ & t < t_{\text{O,start}} \\ -t\zeta + t_{\text{O,end}}\zeta + T_+ & t > t_{\text{O,end}} \end{cases} \quad (18)$$

Where  $T_+$  is the mean of all temperatures above  $0^\circ\text{C}$  and  $t_{\text{O,start}}, t_{\text{O,end}}$  are the days when summer starts and ends. At the K-transect we assumed ~~a start of summer of that the summer starts on the~~ first of May and ends at on first of September. The non-summer temperatures are defined by the slope  $\zeta$ . This is a parameterisation of temperature with only two parameters, namely the slope and the mean positive temperature  $T_+$ .

The precipitation rate is parameterised with a sinusoidal shape in Eq. (19) where  $\Delta P_{\text{Jul}}$  is the precipitation rate offset in July,  $\bar{P}$  is the mean precipitation rate and  $\mathcal{A}$  are seconds per year:

$$P = \bar{P} + \Delta P_{\text{Jul}} \sin\left(\frac{2t\pi}{\mathcal{A}} + 1.5\pi\right) \quad (19)$$

## 4 Modeling results

### 4.1 KAN\_M in 2010

Figure 5 displays detailed results of simulations of the KAN\_M station in the dark zone of the K-transect in the year 2010. Details of the settings can be seen in Fig. 6c (green colors). Figure 5 shows both simulations which use weather station temperature and MAR- model precipitation in green and with the temperature and precipitation parameterisation in dotted lines. The temperature parameterisation in panel a is based on all the available data from 2009 until end 2012 by fitting the temperature over the entire period with a mean of  $1.39^\circ\text{C}$  and a SD of 0.04. This emphasises the low temperature variability at summer and the good fit of the parameterisation at during the melt period. Panel b shows the daily precipitation

of the MAR model and the parameterisation. Here we use the mean precipitation over the whole measurement period which results in a similar snow depth time-series (panel e) as with the MAR precipitation. Plots c and d show the BC and dust amount in the snowpack and on the ice surface respectively. Note the different scales for the different species and for snow and ice, respectively. The amount of aerosols in the snowpack is building up over time and is released onto the ice surface as the snow is melting, which coincides with superimposed ice formation. As we assumed no aerosol content in superimposed ice the aerosol content drops as a result of missing influx from ice melt and runoff on the ice surface. Superimposed ice exposure can be seen in panel f. Later in the melt season the aerosol amount on the ice surface rises again as englacial aerosols are released and accumulating until it balances with runoff and reaches its equilibrium level again, which is then preserved under the new snow cover until the next melt season.

The simulated maximum amount of BC on the surface is  $0.0510.027 \text{ g m}^{-2}$  and of dust is  $25.8213.98 \text{ g m}^{-2}$ . Hence the amount mass of dust is 502-504 times larger than black carbon.

The time series of the albedo is shown in panel g, for comparison the MAR computed albedo is plotted as a dashed line. In 2010 the simulated ice albedo reduction due to accumulated impurities was 0.11 from the base ice albedo.

## 4.2 Simulations of KAN\_M from 2009 until 2013

Figure 6 presents an overview of different parameter values and model results compared to AWS data. Panel a shows the models with temperature from AWS data and MAR precipitation for each day with four different parameter configurations in panel c. Each one is optimised for a different year. The parameter configurations are the result of optimisation for a specific year. These calibrated models are later applied on the rest of the period. Therefore, the calibrated model can be compared to measurements from the remaining period. Panel b uses the same parameter configurations, but this time the temperature and precipitation are parameterized-parameterised with mean temperatures and precipitations calculated over the whole period.

In the simulations the optimisation of the year ~~The Monte Carlo search for the calibration with data from 2009 was problematic as the autumn snow cover was building up earlier than normal~~ results in a simulation without exposed ice when the MAR precipitation is used (Fig. 6 a). When the same parameters are used in with the constant precipitation (panel b) then ice is exposed in summer. This is because isolated significant snow fall events are not captured when the precipitation is constant. Also the parameters set for this year based on 2009 failed to reproduce the low albedo in 2010 but succeeded partly in 2011 and 2012. This is because the Monte Carlo search for parameters related to ice albedo can not succeed without exposed ice.

### 4.3 Stations S5 in 2011

Figure 7 displays the simulation of station S5 in 2011. Station S5 is located close to the margin at low elevation and therefore experiences more ~~surface melt~~ meltwater runoff than KAN\_M because of higher temperatures there. The parameter setting is shown in Fig. 6c and for the temperature parameterisation the data from 2005 until the end of 2012 is used with the positive temperature of 3.60 °C with a SD of 0.02.

In panel d the aerosol evolution on the ice surface is shown, with an amount of BC on the ice surface of ~~0.017 and 1.84~~ 0.002 and 1.07 g m<sup>-2</sup> dust. Comparing it with the equivalent plot of the KAN\_M station Fig. 5d the different scales have to be taken into account. Although the surface melt is about double here as compared to KAN\_M the aerosol amount is less because of the lower englacial content. A small peak in the dust amount of the ice surface can be seen after the dust content of the snowpack has been deposited on ice. This also emphasises the relative magnitude of aerosols deposited from atmosphere as opposed to melted out aerosols. Since ~~the time with (panel f) duration of exposed~~ superimposed ice is much shorter ~~here (panel f)~~, the time evolution of aerosols does not have the ~~same~~ drop at the beginning ~~when ice is exposed~~ of ice exposure.

The high ice albedos at S5 makes it necessary to set the active fraction of BC and dust to zero. Hence the already low amount of aerosols may be mostly trapped in cryoconite holes and therefore not directly influence the ice albedo anymore.

## 5 Discussion

### 5.1 General

In this paper we have introduced a model of dust and black carbon accumulation on the ice surface and its effect on ice albedo of a melting surface. ~~In order to achieve this goal the~~ The model depends on several parts (see Fig. 3): temperature, precipitation, melt, snow thickness, aerosol accumulation and snow and ice albedo reduction. Each part has its own limitations and assumptions. Since the overall goal was to be applicable for long time-scales, it is desired to use a limited number of input data types and be computationally efficient. Therefore, we parameterised the temperature by a trapezoid shape. This shape follows the measurements ~~reasonable~~ reasonably well especially during the melt season when temperature is important for the calculated melt and hence the resulting melt-out of englacial aerosols. Although at station S5 the start of the summer in 2011 and other years was set too early. Therefore, it may be better to adjust the start and end of summer individually by location or parameterise it with an elevation dependency for example.

The precipitation was directly parameterised by taking via the annual mean as a constant influx over the whole year. ~~This is sufficient to get a comparable snow height evolution as to use the MAR model output~~ This parameterisation delivers similar snow depths as when the MAR precipitation is used, because the annual signal are not ~~effected~~ affected by the high frequency variations. Nevertheless this can not simulate significant summer snowfall which would result in a sudden increase from low ice albedo to high dry snow albedos, as can be seen in the data. This could be realised by coupling the model to a regional climate model which would also allow to account for snow metamorphism via the specific surface area. To study the effect of englacial dust and BC simulations over millennia are required which would make this approach computationally ~~too~~ expensive. Nevertheless to study the long term trend this may not be necessary and the simple parameterisation of temperature and precipitation may be sufficient.

The constant annual cycles of surface albedo in Fig. 6b is not just a result of the fixed temperature and precipitation parameterisation, but also because the englacial dust and

BC concentration was set to be constant in this experiments. On longer time-scales these englacial aerosols concentration would vary as the aerosols are transported from the accumulation to the ablation zone. Therefore, the ice albedo will vary even when the temperature and precipitation parameterisations maintain a constant annual cycle.

## 5.2 Amount of accumulated dust and black carbon

The impurity content on the ice surface is much higher than in the snowpack and in the order of a few grams per square meter which is in the range of observations elsewhere on the Greenland ice sheet (Bøggild et al., 2010; Takeuchi et al., 2014). In our simulations the major contribution to the aerosol content on the ice surface came from outcropping of englacial material. The direct influx of dust and BC from the atmosphere is comparably insignificant at the ice sheet margin for the total amount of impurities. ~~As just~~ Even the amount of aerosols released by melt of one meter of ice ~~is melting at the margin it releases the accumulated amount of aerosols releases aerosols which have been~~ deposited over years or ~~even~~ decades in the accumulation zone. ~~Closer to the equilibrium line, where melt is less, atmospheric and input from the surrounding tundra may be dominating.~~

In order to reach the high impurity mass as seen in observations the daily reduction of the accumulated impurities has to be in the order of one per mille. This low value may be a result of slow movement of cryoconite on exposed ice ~~surface surfaces~~, as has been measured on Longyearbreen, Svalbard (Irvine-Fynn et al., 2011) and results in a long residence time of impurities once its exposed on the ice surface or in cryoconite holes. It takes more than 56 years in order to reduce from 30 to below one  $\text{g m}^{-2}$  by assuming 60 days with exposed ice and exponential decay with one per mille per day.

In our simulations of station KAN\_M in the ablation zone the total amount of impurities was dominated by mineral dust. It contributed 500 times more mass than black carbon. We omitted organic matter which has a low mass-density compared to dust and contributed only about 5 % (Bøggild et al., 2010; Wientjes et al., 2011; Takeuchi et al., 2014) to measurement of total mass. Nevertheless it still may have a significant effect on albedo by being more effective per unit mass than dust. ~~As is BC which~~ BC is 100 (Warren and Wiscombe, 1980)

to 200 (Gardner and Sharp, 2010) times more absorbent by mass than dust. Since the cores taken by Wientjes et al. (2011) ~~where were~~ not analysed for its mineral dust content we choose the englacial dust value of  $2000 \text{ ng g}^{-1}$ . This is a value of dust concentration from the NGRIP ice core by Ruth (2007) for the late pleistocene. Although the ~~age of the ice by G14 dating ice is of Holocene age~~, and ranges from 3071 (BP1950) to modern (Wientjes et al., 2012), ~~and is therefore Holocene~~. Dust concentration of the Holocene in ice cores is about 100 times lower (Steffensen, 1997). Therefore, we also tested the accumulation with just  $20 \text{ ng g}^{-1}$  at KAN\_M and together with ~~a an about 0.2~~ higher active fraction of ~~0.6~~ similar albedo values can be reached although with a much lower total impurity amount of below one  $\text{g m}^{-2}$ . Wientjes et al. (2012) explained the higher concentration by a period of enhanced eolian activity in the Holocene. The source of dust of deep cores in the ice sheet interior revealed Asia as the main source of dust (Biscaye et al., 1997; Svensson et al., 2000) although cores from local ice caps (Renland and Hans Tausend) were found to have a more local source (Bory et al., 2003). There might be a “threshold elevation” up to which local dust ~~is contributing contributes significantly~~ and above that elevation large scale transport ~~is dominating and transporting dust~~ from other continents ~~dominates the aerosol transport~~ to the GrIS interior.

A detailed study of relative amount of impurities is required to further investigate the concentration to mass of each species. Our simulations give a quantitative estimate of the involved dynamics and the relative importance of outcropping of aerosols. The amount of outcropped material is relative robust, as it is depending on the amount of melt which simulations yielding similar results as observations (Van As et al., 2012) (see Fig. S1 in the Supplement) and the englacial concentration which resulted in a total amount in comparable to observations.

### 5.3 Reduced albedo at KAN\_M after 2009

The albedo in summer 2009 was around 0.6 while in 2010 (see Fig. 6a) it dropped to around 0.4 and reached even lower values in the following years. We speculate that this

may have been caused by the high amount of outcropped dust and BC due to **higher temperatures**more surface melt.

The year 2009 was in the range of values between 1974–2010 (Van As et al., 2012) at the Kangerlussuaq station while the average temperature in 2010 was 4.9 K above average. At the KAN\_M station location at higher elevation the average temperature in 2010 was 4.4 K **warmer**higher than in 2009, which together with low precipitation~~resulted in enhanced~~, resulted in a more negative surface mass balance of  $-1.93$  m w.e. ~~while~~. While in 2009 it was only  $-0.22$  m w.e. (Van de Wal et al., 2012) at the closely located Site 8. In 2011 the temperatures were low again, even lower than in 2009 but the surface mass balance remained low ( $-1.89$ ) due to the low albedo. This effect might be persisted for the upcoming years if the surface is not cleaned by a local event.

In addition the specific surface area of ice might have increases from 2009 to 2010. In order to reach an albedo higher than 0.6, according to Equation 13, the specific surface area must be greater than  $6.3 \text{ cm}^2 \text{ g}^{-1}$ . The specific surface area in 2009 must have been above that value, since ice was exposed and the albedo was above 0.6. When using the SSA of 6.3 in 2011, with the otherwise unchanged parameters, even an active fraction of 1 is not enough to reduce the ice albedo to the level measured in 2010. This indicates that also the specific surface area has changed.

## 6 Conclusions

We developed a computationally efficient surface albedo model which takes the accumulation of black carbon (BC) and mineral dust into account and **validated**tested it on the K-Transect in western Greenland. The accumulation model calculates release of englacial material which was found to be the main source of impurity mass of which the main contributor was dust. Our simulations suggest a limited loss of impurities on a daily basis in the range of one per-mille which results in a multi-decadal residence time. This indicates that single extreme dust and BC deposition events would affect the glacier ice albedo for decades.

Future improvements of the model depend on a detailed understanding of the affect-effect of impurity species on ice albedo since black carbon is to our knowledge entirely studied on snow (Hodson, 2014) (Hodson, 2014; Pirazzini, 2009). The key difference of impurity interaction on ice as opposed to snow are the driving surface processes. In this study we lumped all this process together into one parameter – the active fraction. This is a very powerful parameter determining the total impact of impurities on ice albedo and additional data is required to derive a physical model of the active fraction. The surface distribution and interaction with cryoconite holes needs to be better understood since it influences the residence-time of each species. For that purpose cameras on automatic weather stations could be useful as well as routinely taking-taken surface samples at surface mass balance sites. In addition the microbiological activity and its direct effect on ice albedo has yet to be fully understood and once it is it can easily be incorporated into the model framework. Moreover, the specific surface of the ice i.e. the ablation crust is an important parameter which needs to be quantified.

Together with a transport scheme of englacial aerosols the present albedo model can be used to study the long term effects of natural and anthropogenic aerosols on future melt of glaciers and ice sheets. This model framework could be applied to further investigate the role of black carbon on the termination of the little ice age in the alps for example.

The full benefit of the present model is on long term projections of future sea level rise and can shed light on the way the Greenland ice sheet will be influenced by the dust and BC currently transported toward the ablation zone inside the ice. As the current source of BC in Greenland is probably Asia the total englacial amount stored in Greenland is still increasing. Fortunately due to modernisation the emissions are expected to decrease until 2030 (Streets, 2007). Nevertheless, the full effect of past emissions still remains to come into effect, as the particles that melt free at the ice sheet margin, released by melt accumulate and impact the melt-for-long-time-to-come magnitude of melt for a long period.

**The Supplement related to this article is available online at  
doi:10.5194/tcd-0-1-2015-supplement.**

*Acknowledgements.* We would like to thank IMAU and GEUS for providing AWS data of the K-Transect. Ralf Greve who helped in improving the manuscript. This publication is contribution number 60 of the Nordic Centre of Excellence SVALI, “Stability and Variations of Arctic Land Ice”, funded by the Nordic Top-level Research Initiative (TRI).

## References

- Bales, R. C., Guo, Q., Shen, D., McConnell, J. R., Du, G., Burkhart, J. F., Spikes, V. B., Hanna, E., and Cappelen, J.: Annual accumulation for Greenland updated using ice core data developed during 2000–2006 and analysis of daily coastal meteorological data, *J. Geophys. Res.*, 114, D06116, doi:10.1029/2008JD011208, 2009.
- Bauer, S. E., Bausch, A., Nazarenko, L., Tsigaridis, K., Xu, B., Edwards, R., Bisiaux, M., and McConnell, J.: Historical and future black carbon deposition on the three ice caps: ice core measurements and model simulations from 1850 to 2100, *J. Geophys. Res.-Atmos.*, 118, 7948–7961, doi:10.1002/jgrd.50612, 2013.
- Biscaye, P. E., Grousset, F. E., Revel, M., van der Gaast, S., Zielinski, G. A., Vaars, A., and Kukla, G.: Asian provenance of glacial dust (stage 2) in the Greenland ice sheet project 2 ice core, summit, Greenland, *J. Geophys. Res.-Oceans*, 102, 26765–26781, doi:10.1029/97JC01249, 1997.
- Bøggild, C. E., Oerter, H., and Tukiainen, T.: Increased ablation of Wisconsin ice in eastern north Greenland: observations and modelling, *Ann. Glaciol.*, 23, 144–148, 1996.
- Bøggild, C. E., Brandt, R., Brown, K., and Warren, S. G.: The ablation zone in northeast Greenland: ice types, albedos and impurities, *J. Glaciol.*, 56, 101–113, doi:10.3189/002214310791190776, 2010.
- Bory, A., Biscaye, P., Piotrowski, A., and Steffensen, J. P.: Regional variability of ice core dust composition and provenance in Greenland, *Geochem. Geophys. Geosy.*, 4, 1107, doi:10.1029/2003GC000627, 2003.
- Bougamont, M., Bamber, J. L., and Greuell, W.: A surface mass balance model for the Greenland Ice Sheet, *J. Geophys. Res.*, 110, F04018, doi:10.1029/2005JF000348, 2005.
- Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, *The Cryosphere*, 6, 821–839, doi:10.5194/tc-6-821-2012, 2012.

- Calanca, P., Gilgen, H., Ekholm, S., and Ohmura, A.: Gridded temperature and accumulation distributions for Greenland for use in cryospheric models, *Ann. Glaciol.*, 31, 118–120, doi:10.3189/172756400781820345, 2000.
- Cuffey, K. M. and Paterson, W. S. B.: *The Physics of Glaciers*, 4th Edn., Elsevier Inc., Burlington and Oxford, 2010.
- [Dadic, R., Mullen, P. C., Schneebeli, M., Brandt, R., and Warren, S. G.: Effects of bubbles, cracks, and volcanic tephra on the spectral albedo of bare ice near the Transantarctic Mountains: Implications for sea glaciers on Snowball Earth, \*Journal of Geophysical Research-Earth Surface\*, 118, 1658–1676, doi:10.1002/jgrf.20098, 2013.](#)
- Doherty, S. J., Grenfell, T. C., Forsström, S., Hegg, D. L., Brandt, R., and Warren, S. G.: Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow, *J. Geophys. Res.-Atmos.*, 118, 5553–5569, doi:10.1002/jgrd.50235, 2013.
- Dolan, A. M., Hunter, S. J., Hill, D. J., Haywood, A. M., Koenig, S. J., Otto-Bliesner, B. L., Abe-Ouchi, A., Bragg, F., Chan, W.-L., Chandler, M. A., Contoux, C., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Ramstein, G., Rosenbloom, N. A., Sohl, L., Stepanek, C., Ueda, H., Yan, Q., and Zhang, Z.: Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the warm Pliocene, *Clim. Past Discuss.*, 10, 3483–3535, 11, 403–424, doi:10.5194/cp-11-403-2015, 2015.
- Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M. J., Angelen, J. H., and Van den Broeke, M. R.: An improved mass budget for the Greenland ice sheet, *Geophys. Res. Lett.*, 41, 866–872, doi:10.1002/(ISSN)1944-8007, 2014.
- Fitzgerald, P. W., Bamber, J. L., Ridley, J. K., and Rougier, J. C.: Exploration of parametric uncertainty in a surface mass balance model applied to the Greenland ice sheet, *J. Geophys. Res.*, 117, F01021, doi:10.1029/2011JF002067, 2012.
- Flanner, M. G. and Zender, C. S.: Linking snowpack microphysics and albedo evolution, *J. Geophys. Res.*, 111, D12208, doi:10.1029/2005JD006834, 2006.
- Gardner, A. and Sharp, M.: A review of snow and ice albedo and the development of a new physically based broadband albedo parameterization, *J. Geophys. Res.*, 115, F01009, doi:10.1029/2009JF001444, 2010.
- Hock, R. and Noetzi, C.: Areal melt and discharge modelling of Storglaciären, Sweden, *Ann. Glaciol.*, 24, 211–217, 1997.
- Hodson, A. J.: Understanding the dynamics of black carbon and associated contaminants in glacial systems, *Wiley Interdisciplinary Reviews: Water*, 1, 141–149, doi:10.1002/wat2.1016, 2014.

- Irvine-Fynn, T. D. L., Bridge, J. W., and Hodson, A. J.: In situ quantification of supraglacial cryoconite morphodynamics using time-lapse imaging: an example from Svalbard, *J. Glaciol.*, 57, 651–657, doi:10.3189/002214311797409695, 2011.
- Janssens, I. and Huybrechts, P.: The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet, *Ann. Glaciol.*, 31, 133–140, doi:10.3189/172756400781819941, 2000.
- Klok, E. J. and Oerlemans, J.: Model study of the spatial distribution of the energy and mass balance of Morteratschgletscher, Switzerland, *J. Glaciol.*, 48, 505–518, doi:10.3189/172756502781831133, 2002.
- Koch, D. and Hansen, J.: Distant origins of Arctic black carbon: a Goddard Institute for Space Studies ModelE experiment, *J. Geophys. Res.*, 110, 4204, 2005.
- Konzelmann, T. and Braithwaite, R.: Variations of ablation, albedo and energy balance at the margin of the Greenland ice sheet, Kronprins Christian Land, eastern north Greenland., *J. Glaciol.*, 41, 174–182, 1995.
- Lei, Y., Zhang, Q., He, K. B., and Streets, D. G.: Primary anthropogenic aerosol emission trends for China, 1990–2005, *Atmos. Chem. Phys.*, 11, 931–954, doi:10.5194/acp-11-931-2011, 2011.
- Liou, K. N.: *An Introduction to Atmospheric Radiation*, Vol. 84, International Geophysics, Academic Press, San Diego and London, 2 Edn., 2002.
- Lu, Z., Zhang, Q., and Streets, D. G.: Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010, *Atmos. Chem. Phys.*, 11, 9839–9864, doi:10.5194/acp-11-9839-2011, 2011.
- Machguth, H., Rastner, P., Bolch, T., Mölg, N., Sørensen, L. S., Aðalgeirsdóttir, G., van Angelen, J. H., Van den Broeke, M. R., and Fettweis, X.: The future sea-level rise contribution of Greenland's glaciers and ice caps, *Environ. Res. Lett.*, 8, 025005, doi:10.1088/1748-9326/8/2/025005, 2013.
- Mahowald, N. M., Kohfeld, K., Hansson, M. E., Balkanski, Y., Harrison, S. P., Prentice, I. C., Schulz, M., and Rodhe, H.: Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments, *J. Geophys. Res.-Atmos.*, 104, 15895–15916, doi:10.1029/1999JD900084, 1999.
- Male, D. H. and Granger, R. J.: Snow surface energy exchange, *Water Resour. Res.*, 17, 609–627, doi:10.1029/WR017i003p00609, 1981.
- Male, D. H. and Gray, D. M. (Eds.): *Handbook of Snow: Principles, Processes, Management and Use*, The Blackburn Press, Caldwell, New Jersey, USA, 1981.

- McConnell, J., Edwards, R., Kok, G., Flanner, M., Zender, C. S., Saltzman, E., Banta, J., Pasteris, D., Carter, M., and Kahl, J.: 20th-century industrial black carbon emissions altered arctic climate forcing, *Science*, 317, 1381, doi:10.1126/science.1144856, 2007.
- Müller, F. and Keeler, C.: Errors in short-term ablation measurements on melting ice surfaces, *J. Glaciol.*, 8, 91–105, 1969.
- Oerlemans, J.: A model for the surface balance of ice masses: Part I: Alpine glaciers, *Zeitschrift für Gletscherkunde und Glacialgeologie*, 27, 63–83, 1991.
- Oerlemans, J.: *Glaciers and Climate Change*, A. A. Balkema Publishers, Lisse; Exton, PA, 2001.
- Oerlemans, J., Giesen, R. H., and Van den Broeke, M. R.: Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland), *J. Glaciol.*, 55, 729–736, doi:10.3189/002214309789470969, 2009.
- Painter, T. H., Flanner, M. G., Kaser, G., Marzeion, B., VanCuren, R. A., and Abdalati, W.: End of the Little Ice Age in the Alps forced by industrial black carbon, *P. Natl. Acad. Sci. USA*, 110, 15216–15221, doi:10.1073/pnas.1302570110, 2013.
- Pirazzini, R.: Challenges in snow and ice albedo parameterizations, *Geophysica*, 45, 41–62, 2009.
- Reeh, N.: Parameterization of melt rate and surface temperature on the Greenland ice sheet, *Polarforschung*, 53, 113–128, 1991.
- Remias, D., Holzinger, A., Aigner, S., and Luetz, C.: Ecophysiology and ultrastructure of *Ancydonema nordenskiöldii* (Zygnematales, Streptophyta), causing brown ice on glaciers in Svalbard (high arctic), *Polar Biol.*, 35, 899–908, doi:10.1007/s00300-011-1135-6, 2012.
- Robinson, A.: Modeling the Greenland Ice Sheet response to climate change in the past and future, Ph. D. thesis, Mathematisch-Naturwissenschaftliche Fakultät der Universität Potsdam, Potsdam, 2011.
- Robinson, A., Calov, R., and Ganopolski, A.: An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change, *The Cryosphere*, 4, 129–144, doi:10.5194/tc-4-129-2010, 2010.
- Robinson, A., Calov, R., and Ganopolski, A.: Greenland ice sheet model parameters constrained using simulations of the Eemian Interglacial, *Clim. Past*, 7, 381–396, doi:10.5194/cp-7-381-2011, 2011.
- Ruth, U.: Dust concentration in the NGRIP ice core, doi:10.1594/PANGAEA.587836, Supplement to: Ruth, U., Bigler, M., Röthlisberger, R., Siggaard-Andersen, M.-L., Kipfstuhl, J., Goto-Azuma, K., Hansson, M. E., Johnsen, S. J., Lu, H., and Steffensen, J. P.: Ice core evidence for a very

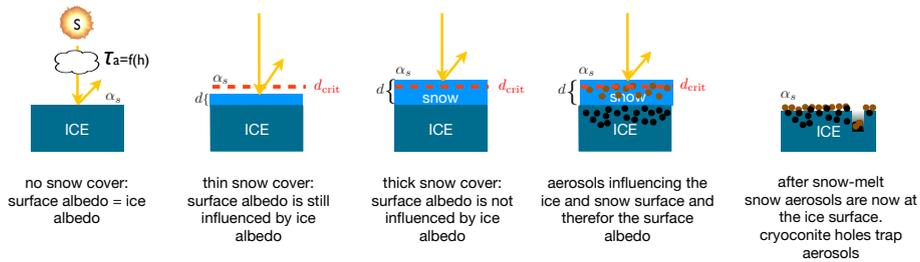
- tight link between North Atlantic and east Asian glacial climate, *Geophys. Res. Lett.*, 34, L03706, doi:10.1029/2006GL027876, 2007.
- Steffensen, J. P.: The size distribution of microparticles from selected segments of the Greenland Ice Core Project ice core representing different climatic periods, *J. Geophys. Res.-Oceans*, 102, 26755–26763, doi:10.1029/97JC01490, 1997.
- Stibal, M., Šabacká, M., and Žárský, J.: Biological processes on glacier and ice sheet surfaces, *Nat. Geosci.*, 5, 771–774, doi:10.1038/ngeo1611, 2012.
- Streets, D. G.: Dissecting future aerosol emissions: warming tendencies and mitigation opportunities, *Climatic Change*, 81, 313–330, 2007.
- Svensson, A., Biscaye, P. E., and Grousset, F. E.: Characterization of late glacial continental dust in the Greenland Ice Core Project ice core, *J. Geophys. Res.*, 105, 4637–4656, 2000.
- Takeuchi, N.: Optical characteristics of cryoconite (surface dust) on glaciers: the relationship between light absorbency and the property of organic matter contained in the cryoconite, *Ann. Glaciol.*, 34, 409–414, doi:10.3189/172756402781817743, 2002.
- Takeuchi, N., Kohshima, S., and Seko, K.: Structure, formation, and darkening process of albedo-reducing material (cryoconite) on a Himalayan glacier: a granular algal mat growing on the glacier, *Arct. Antarct. Alp. Res.*, 33, 115–122, doi:10.2307/1552211, 2001.
- Takeuchi, N., Nagatsuka, N., Uetake, J., and Shimada, R.: Spatial variations in impurities (cryoconite) on glaciers in northwest Greenland, *Bulletin of Glaciological Research*, 32, 85–94, doi:10.5331/bgr.32.85, 2014.
- Tedesco, M., Fettweis, X., Van den Broeke, M. R., Van de Wal, R. S. W., Smeets, C. J. P. P., Van de Berg, W. J., Serreze, M. C., and Box, J. E.: The role of albedo and accumulation in the 2010 melting record in Greenland, *Environ. Res. Lett.*, 6, 014005, doi:10.1088/1748-9326/6/1/014005, 2011.
- Tedesco, M., Fettweis, X., Alexander, P., Green, G., and Datta, T.: MAR Greenland Outputs from Outputs 2005-01-01 to 2013-01-01 ver. 3.2, CCNY Digital Archive, online, 2014.
- van Angelen, J. H., Lenaerts, J. T. M., Lhermitte, S., Fettweis, X., Kuipers Munneke, P., van den Broeke, M. R., van Meijgaard, E., and Smeets, C. J. P. P.: Sensitivity of Greenland Ice Sheet surface mass balance to surface albedo parameterization: a study with a regional climate model, *The Cryosphere*, 6, 1175–1186, doi:10.5194/tc-6-1175-2012, 2012.
- Van As, D., Van den Broeke, M. R., Reijmer, C., and Van de Wal, R. S. W.: The summer surface energy balance of the high Antarctic plateau, *Bound.-Lay. Meteorol.*, 115, 289–317, doi:10.1007/s10546-004-4631-1, 2005.

- Van As, D., Fausto, R. S., and Team, P. P.: Programme for Monitoring of the Greenland Ice Sheet (PROMICE): first temperature and ablation records, *Geol. Surv. Den. Greenl.*, 73–76, 2011.
- van As, D., Hubbard, A. L., Hasholt, B., Mikkelsen, A. B., van den Broeke, M. R., and Fausto, R. S.: Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations, *The Cryosphere*, 6, 199–209, doi:10.5194/tc-6-199-2012, 2012.
- Van de Wal, R. S. W.: Ice and Climate, Ph. D. thesis, Utrecht University, Utrecht, 1992.
- Van de Wal, R. S. W., Greuell, W., Van den Broeke, M. R., Reijmer, C. H., and Oerlemans, J.: Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, West Greenland, *Ann. Glaciol.*, 42, 311–316, doi:10.3189/172756405781812529, 2005.
- Van de Wal, R. S. W., Boot, W., Smeets, C. J. P. P., Snellen, H., van den Broeke, M. R., and Oerlemans, J.: Twenty-one years of mass balance observations along the K-transect, West Greenland, *Earth Syst. Sci. Data*, 4, 31–35, doi:10.5194/essd-4-31-2012, 2012.
- Van den Berg, J., Van de Wal, R. S. W., and Oerlemans, J.: A mass balance model for the Eurasian ice sheet for the last 120 000 years, *Global Planet. Change*, 61, 194–208, doi:10.1016/j.gloplacha.2007.08.015, 2008.
- Van den Broeke, M. R., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning recent Greenland mass loss, *Science*, 326, 984–986, doi:10.1126/science.1178176, 2009a.
- Van den Broeke, M. R., Smeets, P., and Ettema, J.: Surface layer climate and turbulent exchange in the ablation zone of the west Greenland ice sheet, *Int. J. Climatol.*, 29, 2309–2323, doi:10.1002/joc.1815, 2009b.
- Vaughan, D. G., Comiso, J. C., Allison, I., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: cryosphere, in: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 317–382, 2013.
- Warren, S. G. and Wiscombe, W. J.: A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols, *J. Atmos. Sci.*, 37, 2734–2745, 1980.
- Wientjes, I. G. M. and Oerlemans, J.: An explanation for the dark region in the western melt zone of the Greenland ice sheet, *The Cryosphere*, 4, 261–268, doi:10.5194/tc-4-261-2010, 2010.

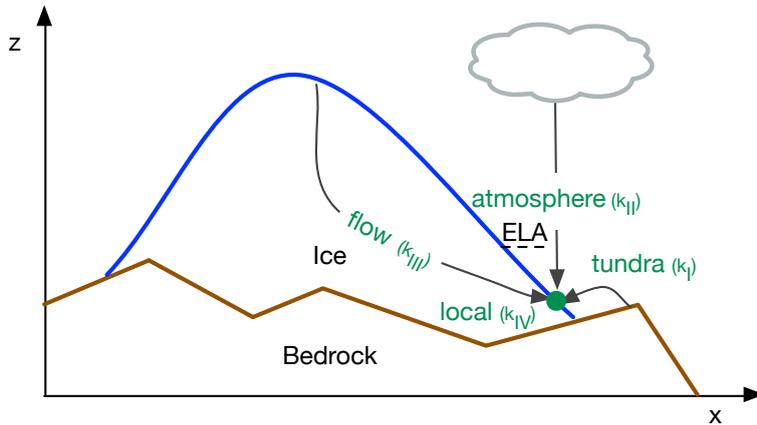
- Wientjes, I. G. M., Van de Wal, R. S. W., Reichert, G. J., Sluijs, A., and Oerlemans, J.: Dust from the dark region in the western ablation zone of the Greenland ice sheet, *The Cryosphere*, 5, 589–601, doi:10.5194/tc-5-589-2011, 2011.
- Wientjes, I. G. M., Van de Wal, R. S. W., Schwikowski, M., Zapf, A., Fahrni, S., and Wacker, L.: Carbonaceous particles reveal that Late Holocene dust causes the dark region in the western ablation zone of the Greenland ice sheet, *J. Glaciol.*, 58, 787–794, doi:10.3189/2012JoG11J165, 2012.
- Yallop, M. L., Anesio, A. M., Perkins, R. G., Cook, J., Telling, J., Fagan, D., MacFarlane, J., Stibal, M., Barker, G., Bellas, C., Hodson, A., Tranter, M., Wadham, J., and Roberts, N. W.: Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet, *ISME J.*, 6, 2302–2313, doi:10.1038/ismej.2012.107, 2012.
- Zuo, Z. and Oerlemans, J.: Modelling albedo and specific balance of the Greenland ice sheet: calculations for the Sondre Stromfjord transect, *J. Glaciol.*, 42, 305–317, 1996.

**Table 1.** Standard physical parameters.

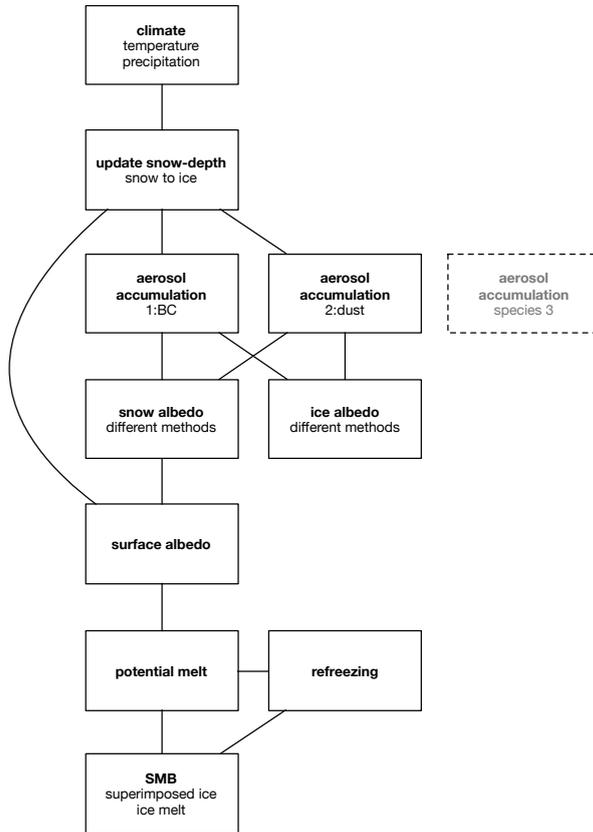
Symbol	Constant	Value	Unit
$\rho_{ice}$	Density of ice	910	$\text{kg m}^{-3}$
$\rho_w$	Density of water	1000	$\text{kg m}^{-3}$
$\mathcal{A}$	Seconds per year	31 556 926	–
$r_{max}$	Refreezing fraction	0.6	–
$t_{\odot, start}$	Start of summer	121	day of the year
$t_{\odot, end}$	End of summer	244	day of the year
$\lambda$	Long-wave radiation coefficient	10	$\text{W m}^{-2} \text{K}^{-1}$
$c$	Short-wave radiation and sensible heat flux constant	–55	$\text{W m}^{-2}$
$r_{max}$	Refreezing fraction	0.6	–
$L_m$	Latent heat for melting of ice	334 000	J kg
$d_{eff}$	Effective depth on ice	5	m



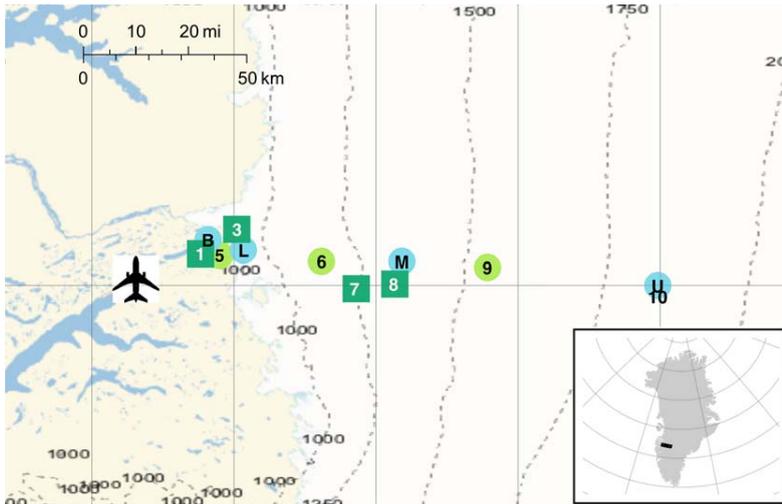
**Figure 1.** The relationship between ice albedo, snow albedo and aerosol concentration to surface albedo. As ice is exposed to melting, englacial aerosols are released and accumulate on the surface. Some impurities on the ice surface are trapped in cryoconite holes and are therefore not directly contributing to a lower surface albedo (Bøggild et al., 2010). In addition microbiological activity can produce dark material on the snow and ice surface and can enhance the albedo reduction by aggregating the impurities.



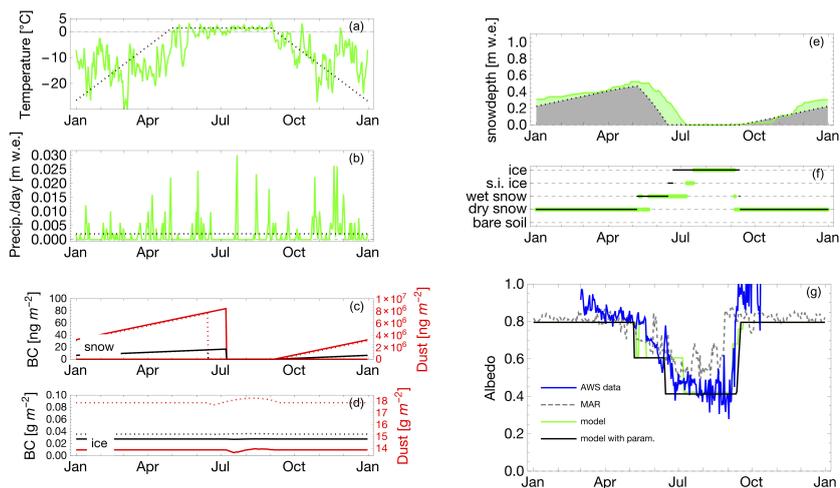
**Figure 2.** Cross section through an ice sheet: four different mechanisms of aerosol transport to the ablation zone. ELA stands for equilibrium line altitude.



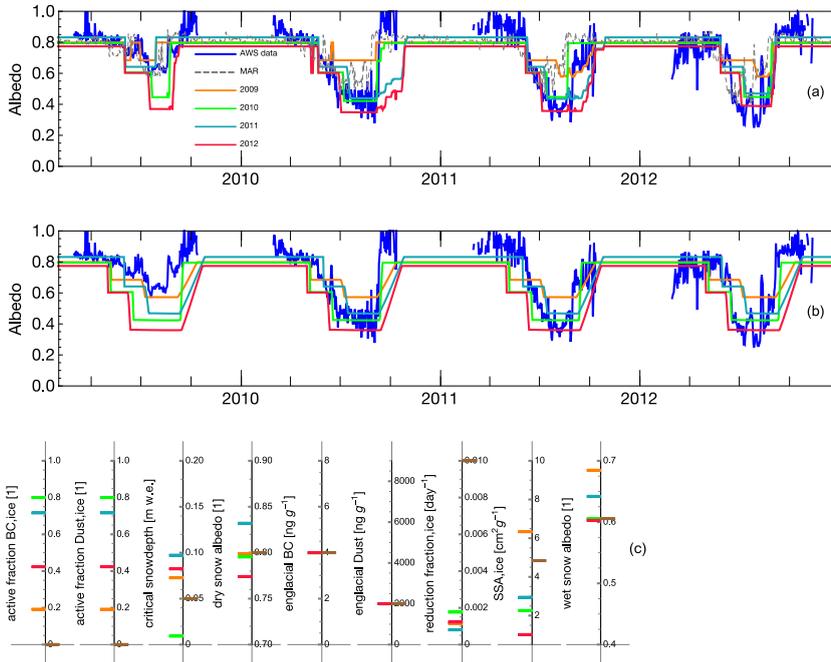
**Figure 3.** Flow chart of the surface mass balance model inside a loop which is solved for each time-step. Ultimately resulting in an annual SMB which can be used as boundary condition in an ice sheet model.



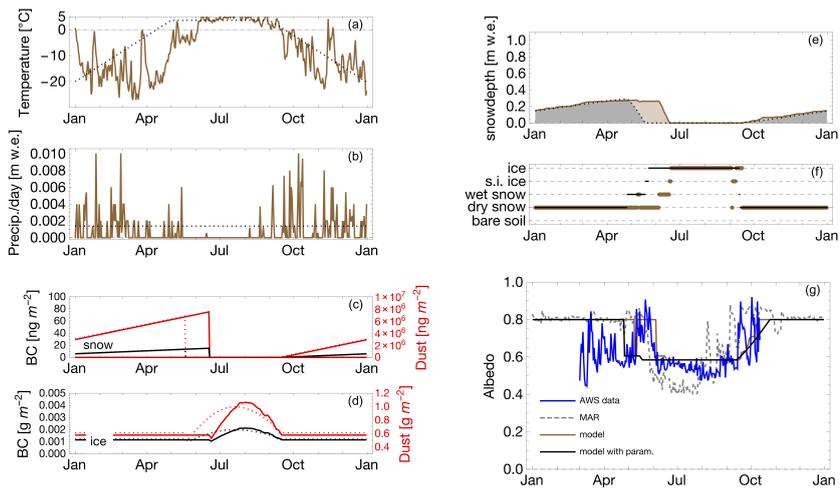
**Figure 4.** Weather stations and sampling sites at the K-transect on western Greenland. The airplane symbol marks the Kangerlussuaq airport. Blue circles mark the PROMICE automatic weather stations operated by GEUS and the green circles mark the ones operated by IMAU. The squares mark additional mass balance sites where ice samples have been taken (Wientjes et al., 2012). Station 9 is located near the equilibrium line and sites 6, 7, 8 and M are located in the dark region with lower albedos.



**Figure 5.** Detailed result of KAN\_M station in 2010 with a simulation after spin-up using precipitation from MAR and temperature from the weather station, shown in green and with temperature and precipitation parameterisation (dotted black). Temperature in (a), daily precipitation in (b). Evolution of dust (red) and BC (black) amount in the snow pack and on the ice surface are shown in (c, d). The snow depth evolution in (e) together with the surface type (f) and aerosol content determine the surface albedo evolution in (g).



**Figure 6.** Albedo evolution of the KAN\_M station over the years 2009 until the end of 2012. Panels (a, b) show AWS data in blue and [simulations with different parameter sets \(c\)](#) in addition to simulations [from the MAR model](#). The [parameters are optimised for different years model is calibrate with data from one year](#) and then [used applied to simulate the entire rest of the period](#). In (a) the precipitation comes from [the MAR model output](#) and the temperature from AWS data and in (b) those are parameterised. [The simulations in panel \(b\) use the same parameter as in panel \(b\)](#). Panel (c) shows the range of settings [of the calibrated parameters](#) for each year and for Station S5 in brown on the right side of the scales.



**Figure 7.** Details of station S5 in the year 2011 with the same plot arrangement as in Fig. 5.