

***Interactive comment on “The influence of snow grain size and impurities on the vertical profiles of actinic flux and associated  $\text{NO}_x$  emissions on the Antarctic and Greenland ice sheets” by M. C. Zatzko et al.***

**M. C. Zatzko et al.**

mzatzko@uw.edu

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Zatzko\_ACP\_2012\_211 Response to Hans-Werner Jacobi's (Reviewer 1) comments:

Dr. Jacobi, thank you for your comments. Please see our responses to your comments below.

Overall Comments: R1C0a: For the transport of  $\text{NO}_x$  from the snowpack to the atmosphere, the authors consider two processes: diffusion and wind-pumping. Based on available parameterizations for these processes the authors obtain lifetimes for  $\text{NO}_x$  due to the transport to the atmosphere called  $\tau_{\text{escape}}$ . This approach would make sense if the  $\text{NO}_x$  concentrations in the firn air would always be higher than in the am-

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bient air. However, as described on p. 15761f the authors need to assume profiles of NO<sub>x</sub> (and other trace gases) for the calculation of the chemical lifetimes. They used observed ambient concentrations scaled to the actinic flux at 305 nm. This leads to an exponential decrease of NO<sub>x</sub> concentrations in the firn air (p. 15769, l. 28f). By the way the few available firn air measurements of NO and NO<sub>2</sub>, but also of other reactive trace gases indicate that this is normally not the case [e.g. Jacobi et al., 2004; Helmig et al., 2009]. Nevertheless, as a result of the assumed profile all transport processes would lead to a downward flux of NO<sub>x</sub> deeper into the snow and no NO<sub>x</sub> would ever escape the snowpack meaning that the calculated  $\tau_{\text{escape}}$  becomes useless for NO<sub>x</sub>.

We agree that assuming an exponential decay of NO and NO<sub>2</sub> in the snow is not appropriate and have removed this approach from the study.

R1C0b: In a second approach, the authors use profiles for NO<sub>x</sub> comparable to those obtained in a previous modeling study at Summit [Thomas et al., 2011]. In this case NO shows a maximum somewhere between 5 and 10 cm depth, while NO<sub>2</sub> remains constant throughout the snowpack. Such a profile causes a similar problem regarding the direction of the fluxes. In this case only the firn air above the NO<sub>x</sub> maximum contributes to an upward flux leading to an escape of NO<sub>x</sub> from the firn air to the atmosphere. At depths below the maximum, the NO<sub>x</sub> flux should again be directed downwards into the snow making the escape of NO<sub>x</sub> from this region impossible.

The chemical profiles calculated in the Thomas et al. [2011] study suggest that the concentration of NO<sub>2</sub>, NO, BrO, and OH are higher in the snow compared to the atmosphere until a depth of 20-30 cm. The profiles suggest that diffusion towards the atmosphere from the snow occurs above the depth of the peak concentration (20-30 cm), which is roughly 1-2 e-folding depths depending on snowpack impurity concentration. This is discussed in section 3.4.

R1C0c: Although I am not an expert in that field I believe that at least in the atmosphere mechanisms for counter-gradient fluxes exist. Possibly the wind-pumping mechanism

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can cause such a counter gradient fluxes? But that needs to be verified and discussed in detail. In any case, the diffusion mechanism will certainly lead to a direction of the NO<sub>x</sub> flux according to the gradient. Thus, even if the wind-pumping may help to transport the NO<sub>x</sub> from deeper layers to the ambient air, the diffusion would in any case cause a flux in the different direction.

Due to the uncertainty in the profiles of NO<sub>x</sub> concentration in the snowpack interstitial air, we focus our analysis of the escape lifetime of NO<sub>x</sub> on wind pumping, which does not depend on NO<sub>x</sub> concentrations. Ignoring diffusion does not change our conclusions since wind pumping dominates the escape lifetime throughout most of the photochemically active zone. Even without diffusion, wind pumping of NO<sub>x</sub> from the snowpack to the atmosphere is still dominant compared to NO<sub>x</sub> decay to HNO<sub>3</sub> when base-case conditions are assumed for variables used to calculate the wind pumping and chemical lifetimes (see Table 3 and Table 4). Including diffusion in addition to wind pumping will further reduce the escape lifetime if the concentration in the snowpack is greater than in the overlying atmosphere. Our NO<sub>x</sub> lifetime comparison results remain qualitative, but do suggest that NO<sub>x</sub> is efficiently ventilated to the overlying atmosphere, in line with assumptions made in previous studies. We have discussed these issues in the last paragraph of section 3.4.

R1C0d: Moreover, equation (30) can be regarded as an integrated initial NO<sub>x</sub> production rate in the snow, but not as flux out of the snowpack because reactions in the condensed phase of the snow can already reduce the fraction of NO<sub>x</sub> that is transferred to the adjacent firn air.

In section 2.5, we mention that equation 26 (equation 30 in old manuscript) calculates the potential flux of NO<sub>x</sub> from the snow. It is a potential flux of NO<sub>x</sub> from the snow because we have assumed that all nitrate is available for photolysis in this study and that all NO<sub>x</sub> produced is transferred to the adjacent firn air.

R1C0e: In summary, with an exponential decrease of NO<sub>x</sub> in the firn air the escape to

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the atmosphere is only possible with the assumption of a counter-gradient flux, which is in my opinion highly uncertain. Assuming a profile with an NO<sub>x</sub> maximum at a certain depth constrains the snow layer from which the NO<sub>x</sub> can escape to the depth of this maximum. However, this maximum is not well constrained by field measurements, only by the modeling study of Thomas et al. for conditions at Summit. Due to the different conditions that can impact the NO<sub>x</sub> profile (like e-folding depths!) I doubt that the simulated profiles at Summit can directly be applied to conditions in Antarctica as was done by the authors. Overall, I recommend that the authors remove part (3) from the manuscript (also because I find that their calculations of the chemical lifetimes of NO<sub>x</sub> in the firn air are very uncertain). In my opinion, part (1) and (2) can constitute a reasonable manuscript acceptable for publication after considering the further comments below. If the authors want to retain part (3), I find it only publishable if these estimates are limited to Summit with the constraints described above for the NO<sub>x</sub> flux. In this case the authors may rely on the simulated firn air profiles from the Thomas et al. paper.

We now limit our NO<sub>x</sub> lifetime analysis to Summit using the calculated firn air profiles from Thomas et al., [2011].

Major Comments: R1C1: Introduction: The Introduction is not well written and contains several smaller and bigger formal and organizational errors.

R1C1a-g address changes that we have made to the Introduction.

R1C1a: In my opinion NO<sub>2</sub> cannot be considered as an oxidant (p. 15746, l.7)

We originally included NO<sub>2</sub> in the list of oxidants because it is a precursor to O<sub>3</sub> formation. To be clear, we have removed NO<sub>2</sub> from the oxidant category in section 1, paragraph 1.

R1C1b: The preservation of H<sub>2</sub>O<sub>2</sub> in ice cores depends on physical processes and accumulation [McConnell et al., 1998; Hutterli et al., 2003], if snow photochemistry plays a role for the preservation of organics remains to be shown (p.15746, l. 14-15).

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We no longer state that organics are trace species in ice cores that can have their preservation altered by photochemical reactions, but there is evidence that the preservation of H<sub>2</sub>O<sub>2</sub> in ice cores is altered by photochemical processes (see Lamarque et al. [2011]). See section 1, paragraph 1 for changes.

R1C1c: Lines 1-3 on page 15747 repeat the authors' view of the NO<sub>x</sub>-HNO<sub>3</sub> cycling in the snow-atmosphere system already described at the beginning of the same paragraph. By the way, this is one major point the manuscripts tries to address by comparing the NO<sub>x</sub> lifetimes due to transport and potential chemical reactions inside the firn air (chapters 2.4 and 3.4), while the introduction already gives the final view of the authors. If and how much of the NO<sub>x</sub> will be emitted to the atmosphere before it is oxidized to HNO<sub>3</sub> remains rather uncertain (see comment above).

Thank you for noticing this repetition. We have removed these lines from the section 1, paragraph 2.

R1C1d: The definitions of actinic flux and e-folding depth (p. 15747, l. 15-16 and p. 15748, l. 7-8) are not well placed.

We have moved the definition of actinic flux and e-folding depth into section 1, paragraph 3, which is the paragraph that describes previous process-based modeling studies.

R1C1e: The description starting on P. 15747, l. 22 of the results of the calculations presented by Wolff et al. (2002) using the now revised absorption coefficients of ice can be much shortened since the cited field measurements also indicate that the obtained e-folding depth were underestimated.

We have taken out several of the sentences in section 1, paragraph 3 that described why the Wolff et al. [2002] study underestimated the e-folding depth of actinic flux in snow.

R1C1f: First measurements of HULIS in arctic snow are now available [Voisin et al.,

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2012] (p. 15748, l. 22-23).

We have now cited the Voisin et al. [2012] study in this paper (section 1, paragraph 4)

R1C1g: The description of the collection and analysis (p. 15748, l. 24ff) can be shortened because it is repeated in more detail in paragraph 2 (where it belongs!).

We have removed several sentences that describe impurity collection and analysis (section 1, paragraph 5).

R1C2a: The authors only provide a rough comparison of their results with the measurements by France et al. [2011] at Dome C. However, the available measurements are much more detailed. For example, France et al. [2011] provide observed wavelength-dependent e-folding depths for different snow types. Are these reproduced by the proposed parameterizations using reasonable assumptions about the snow grain size?

We have compared the measured e-folding depths near the station at Dome C reported in France et al. [2011] to e-folding depths calculated using our actinic flux parameterization. Table 1 (below) shows the e-folding depths measured in France et al. [2011], which have an uncertainty of  $\pm 20\%$ . We have assumed diffuse sky conditions and used the detailed Dome C snow grain radius and density stratigraphy from Gallet et al. [2011] because there is not detailed vertical grain size information France et al. [2011] and it is unclear whether the grain size reported in France et al. [2011] is the snow grain diameter or the radiation equivalent ice grain radius. Further, there is disagreement between the grain sizes reported in France et al. [2011] and Gallet et al. [2011], regardless of which “grain size” definition we assume that they mean. We have used the average density profile measured by Gallet et al. [2011] near Dome C station for all comparisons, because variations in density are considerably smaller than variations in grain size. We calculate the e-folding depth for various snow BC concentrations using three different re profiles from Gallet et al. [2011]; the mean profile reported and two “extreme” profiles based upon Figure 4 in Gallet et al. [2011] (see Table 2). During comparison, we vary BC concentrations from 1-5 ng g<sup>-1</sup> because it is unclear

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how much BC was in the snow near Dome C station during the measurement period. We specifically calculate the e-folding depth using  $CBC = 3.3 \text{ ng g}^{-1}$  because it was the average concentration measured near Dome C station by Warren et al. [2006]. For all comparisons, we assume that nonBC material is responsible for 87% of the absorption at  $\lambda=305$  and 70% at  $\lambda=400$  nm, which is the  $f_{\text{nonBC}}$  calculated from our snow samples collected near Dome C station. Using these assumptions, there is good agreement between the measured e-folding depths at Dome C by France et al. and the e-folding depths calculated using our parameterization for  $CBC=3.3\text{-}5 \text{ ng g}^{-1}$ .

R1C2b: Similarly, at Summit measurements of the nitrate photolysis rates were performed within the snowpack using actinometry [Peterson et al, 2002; Qiu et al, 2002].

Qiu calculates nitrate photolysis rates based upon chemical actinometry at 305 nm for two-hour periods near noon in mid-June at Summit. For comparison, we use a combination of direct and diffuse downwelling radiation from GEOS-Chem to determine the surface irradiance at Summit in mid-June ( $2.4 \times 10^{14} \text{ photons cm}^{-2} \text{ s}^{-1}$ ). The value of downwelling irradiance used by Qiu et al. [2002] is unknown, the absorption cross-section used is  $2.7 \times 10^{-20} \text{ cm}^2 \text{ molec}^{-1}$ , and the quantum yield used is 0.017. We multiply the actinic flux at various depths in the snowpack by the same absorption cross-section and quantum yield used by Qiu et al. [2002] to calculate the nitrate photolysis rate in the snow as a function of depth. Table 3 compares the nitrate photolysis rates calculated by Qiu et al. [2002] (pit 4) to our calculated nitrate photolysis rates. The measured and calculated photolysis rates agree within 29%.

R1C2c: How do these measurements compare to the proposed parameterization and the Monte-Carlo based simulations by Peterson et al. [2002]?

The normalized actinic flux profile calculated using our parameterization can be compared to the normalized actinic flux profiles at Summit, Greenland calculated with a Monte-Carlo radiative transfer model described in Peterson et al. [2002]. We compare the normalized actinic flux profiles from Peterson et al. [2002] with calculated normal-

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ized actinic flux profiles using our parameterization in two scenarios: for a homogenous snowpack with snow = 340 kg m<sup>-3</sup> and snow grain thickness (diameter) = 0.25 mm (Table 4) ; a stratified snowpack with snow ranging from 260-390 kg m<sup>-3</sup> and snow grain thickness (diameter) ranging from 0.15-0.3 mm (Table 5). We normalize profiles relative to the actinic flux at the surface (actinic flux at the surface = 1). These normalized actinic flux profiles are compared at  $\lambda = 290$  nm, 350 nm, and 390 nm. Realistically, for both the homogenous and the heterogeneous snowpacks, we expect the actinic flux calculated using our parameterization to decrease more quickly than the actinic flux calculated using the Monte-Carlo approach because the Monte-Carlo approach is for clean snow and does not consider impurities. So for this analysis, we have set the impurities in our parameterization equal to zero. There is good agreement (within 20%) between the Monte-Carlo model and our parameterization for both homogenous and heterogeneous snowpacks.

I have added an Appendix (Appendix C) that describes all three of the above comparisons in order to demonstrate the validity of the parameterization.

R1C3: According to the authors one of the major motivations for this study was the intention to provide a parameterization for the calculation of actinic fluxes and nitrate photolysis rates in the snowpack that can be included in global models (p. 15749, l. 6ff; p. 15754, l. 23ff; p. 15755, l. 13f; p. 15775, l.7ff). However, this statement remains quite imprecise throughout the manuscript. As far as I know most land-surface schemes that are used in global models to represent snow and snow properties do not generate grain size or black carbon concentrations in the snow. Both are crucial variables that are needed for the proposed parameterization. On the other hand the NCAR Community Land Model CLM has been used [e.g. Flanner and Zender, 2006; Flanner et al., 2009] to estimate the impact of BC in the snow on regional and global climate. But to do so they integrated their snow radiation scheme SNICAR in the CLM. As a result, CLM combined with SNICAR delivers full radiative profile in the simulated snowpack making a new parameterization obsolete. Possibly, the authors have the

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application in other models in mind, but they should clearly state for which kind of land surface schemes or models their parameterization can be useful.

We plan to incorporate the snowpack actinic flux parameterization in GEOS-Chem, a global chemical transport model, in order to calculate the flux of NO<sub>x</sub> from snow in polar regions.

The papers you suggested looking at are very complete studies. Flanner uses an empirical relationship for snow microphysics in SNICAR (which is a 2-stream radiative transfer model) when SNICAR is coupled to a global climate model (GCM). It will be useful to compare the GCM coupled to SNICAR with GEOS-Chem once the actinic flux parameterization is included. Using multiple models and methods to study photodenitrification will lead to a more robust understanding of these processes.

There are differences between the SNICAR model and the parameterization, and also some limitations in GEOS-Chem that would prevent a coupling between SNICAR and GEOS-Chem and instead promote inclusion of the parameterization in GEOS-Chem and other chemical transport models. First, the SNICAR model is a full two-stream model while our parameterization is based on a four-stream model, and agrees with the four-stream model within 2 percent. The SNICAR model is more detailed than the parameterization, however, the computational time is likely much longer compared to our parameterization. Our parameterization consists of a dozen equations and all of the variables except irradiance, solar zenith angle, and accumulation rate (used to scale black carbon observations) are either assumed or calculated off-line, making implementation of this parameterization into CTMs simple and straight-forward. We have performed sensitivity studies of variables such as impurities and snow grain size to determine which variables could be assumed and which must be treated with greater care. Although we have not yet done a full comparison of the computational time saved using our parameterization versus a full radiative transfer model, its ease of implementation and accuracy compared to a full radiative transfer model will make it broadly accessible to the global modeling community.

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The parameterization makes use of offline grain size profiles, while the SNICAR model invokes a temperature-dependent snow microphysics empirical relationship to calculate the change in grain size and is a full radiative transfer model. SNICAR is coupled to a GCM that has temperature information at various layers beneath the surface, but GEOS-Chem does not have any sub-surface layers. SNICAR requires information about the temperature in each layer for snow metamorphosis, but since GEOS-Chem does not have sub-surface layers, SNICAR cannot be coupled to GEOS-Chem in the same way that it is coupled to the GCM.

Because GEOS-Chem does not contain snow layer information, we plan to use available observations of black carbon in polar snowpack and scale them by accumulation rate in Antarctica and Greenland. Currently, the parameterization is only valid for snowpacks deeper than 1.5 meters, therefore we will only apply the parameterization to continental regions in Antarctica and Greenland. For radiation equivalent grain size and snow grain density, we plan to use the observations from Gallet et al. [2011] in Antarctica and Albert and Shultz [2002] in Greenland. Gallet et al. [2011] reported re profiles along the transverse from Dome C to DDU, which provides insight as to how the re profile changes with increasing distance from coastal Antarctica. We acknowledge the uncertainties in our planned approach, however, we are looking to get a rough estimate of the NO<sub>x</sub> flux from the snow and must use an approach that is computationally efficient.

Minor Comments: R1C4: On p. 15769, l. 3ff the authors state that the variability in sastrugi dimensions are most important for the escape of NO<sub>x</sub> from the firn air saying also that the impact of the variability of the other parameters are negligible. Please give the range of values used for the other parameters for these tests. For example, the tortuosity of the snow shows a considerable variability and has at the same time a strong impact on the diffusion coefficient of NO<sub>x</sub>.

We have now included the range of values used for permeability, viscosity, snow density, and tortuosity in Table 3 and have made note of where these ranges can be found

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in the text (section 3.4, paragraph 3). In the revised comparison, NO<sub>x</sub> efficiently escapes from the snowpack via windpumping throughout most of the photochemically active zone when base-case conditions are considered and any value of snow density is assumed. But, NO<sub>x</sub> in the photochemically active zone is more likely to convert to HNO<sub>3</sub> rather than escape to the atmosphere for a permeability of  $1 \times 10^{-10}$  or less, a viscosity of  $9 \times 10^{-5}$  or greater, and a sastrugi aspect ratio (height/wavelength) greater than 0.16, when windpumping is the only mechanism considered for NO<sub>x</sub> transport out of the firn interstitial air. We have rewritten much of 3.4, gotten rid of the Figure that compared escape processes, and updated Figures 4 and 5. In Figure 4, we only show results using the chemical profiles at Summit from Thomas et al. [2011]. In Figure 5, we now compare  $\tau_{\text{wind pumping}}$  to  $\tau_{\text{chemical}}$  only at Summit, where  $\tau_{\text{chemical}}$  is calculated using the Thomas et al. [2011] chemical profiles and base-case values for permeability, viscosity, density, and sastrugi dimensions. We have also attempted to make our results more qualitative than quantitative based upon uncertainties, and give more emphasis to the discussion of the uncertainties in section 3.4.

R1C5: The authors assume that all of the nitrate in the snow at South Pole and Dome C is introduced by dry deposition (p. 15764, l. 5f). This is quite unrealistic. Although measurements are very limited, Dibb et al. [2004] demonstrated that at South Pole a newly accumulated surface snow layer showed higher nitrate concentrations than observed in the previous surface layer before. The authors should revisit their assumptions about the fraction of dry and wet deposition of nitrate in Antarctica.

We now no longer use dry and wet deposition to estimate the amount of nitrate available for photolysis in the snow due to the uncertainties surrounding the issue. Instead, we now calculate a “potential” NO<sub>x</sub> flux, where we assume that all nitrate in the snow is available for photolysis (see section 2.5 and 3.5).

R1C6: P. 15764, l. 21: The ratio of BC at Summit and Dome C is rather two than three. Thank you for catching this typo. We have replaced “roughly three” with “over two” in section 3.1, paragraph 2.

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R1C7: P. 15764, l. 23ff: The higher BC concentrations in the snow at Summit could also be caused by a more efficient deposition.

We have now mentioned that the higher BC concentration at Summit could also be caused by a more efficient deposition in section 3.1, paragraph 2.

R1C8: P. 15766, l. 12: Figure 3b shows only the dependence of the actinic flux in the presence of BC, but not nonBC.

Figure 3b does show the dependence of actinic flux in the presence of both BC and nonBC, but this was not clear in the figure or in the figure caption. We have now included the fraction of nonBC absorption compared to total (BC + nonBC) absorption at  $\lambda=305$  nm for each curve in Figure 3, which is noted in the caption and in the accompanying text (section 3.2, paragraph 2).

R1C9: P. 15766, l. 22:  $z = 50$  cm instead of 500 cm? We have meant  $z=500$  cm instead of  $z=50$  cm. We used the mean observed  $r_e$  profile from Gallet et al. [2011] from  $z=0$ cm ( $86 \mu\text{m}$ ) to  $z=50$  cm ( $234 \mu\text{m}$ ). Below 50 cm, we linearly extrapolated the  $r_e$  profile (assuming constant grain growth with depth), which resulted in a value of  $r_e=460 \mu\text{m}$  at  $z=500$  cm. The linear extrapolation of  $r_e$  is uncertain, but we have performed sensitivity studies using extreme  $r_e$  profiles observed by Gallet et al. [2011] ( $r_e=50\text{--}652 \mu\text{m}$  from  $z=0\text{--}50$  cm and  $r_e = 102\text{--}192 \mu\text{m}$  from  $z=0\text{--}50$  cm) and noticed the normalized actinic flux profile (black curve, Figure 3c) decreases with depth more quickly than when  $r_e$  is kept constant at  $500 \mu\text{m}$  and more slowly than when  $r_e$  is kept constant at  $100 \mu\text{m}$  no matter which profile from Gallet et al. [2011] is used.

R1C10: Table 1: From which depth ranges were the samples? I also recommend to give the same information for each sample in a separate table as supplementary material.

The depth ranges are now included in Table 1 and Appendix B. We have included the same information found in Table 1 for each sample in a table in Appendix B.

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Figures 2 to 6: In these figures the scale of the depths ranges from 100 to 300 cm. If the figures are not deleted in a revised manuscript I recommend to make this scale uniform (for example using 200 cm as a bit more than 3 times the largest e-folding depths).

The figures that have remained in the revised manuscript now have uniform scales ranging 0 to 150 cm.

Figure 3b: The actinic flux with  $BC = 0$  is smaller than in the presence of 0.3 ppb or 0.6 ppb BC? This can not be correct.

This figure has been corrected. A value of 1.42 ng g<sup>-1</sup> was accidentally used instead of 0 ng g<sup>-1</sup>.

References: Lamarque, J.-F., McConnell, J. R., Shindell, D. T., Orlando, J. J., Tyndall, G. S.: Understanding the drivers for the 20th century change of hydrogen peroxide in Antarctic ice-cores, *Geophys. Res. Lett.*, 38, L04810, doi:10.1029/2010GL045992, 2011.

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Table 1: E-folding depths measured in snowpacks at Dome C from France et al. [2011]:

<b>snow type</b>	<b>350 nm</b>	<b>400 nm</b>
soft windpack	$z_e = 9$ cm	$z_e = 10$ cm
hard windpack	$z_e = 9$ cm	$z_e = 10$ cm
hoar like	$z_e = 20$ cm	$z_e = 20$ cm

Fig. 1.

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Table 2. E-folding depths calculated for near-station snowpacks at Dome C using vertical density and radiative equivalent ice grain radius profiles from Gallet et al. [2011].

$C_{BC}$ ( $\text{ng g}^{-1}$ )	$\rho_{\text{snow}}$ ( $\text{g cm}^{-3}$ )	$r_e$ ( $\mu\text{m}$ )	350 nm	400 nm
1	0.26-0.36	86-460	$z_e = 19\text{-}21$ cm	$z_e = 23\text{-}27$ cm
3.3			$z_e = 10\text{-}11$ cm	$z_e = 13\text{-}15$ cm
5			$z_e = 8\text{-}9$ cm	$z_e = 10\text{-}12$ cm
1	0.26-0.36	61-654	$z_e = 19\text{-}25$ cm	$z_e = 27\text{-}32$ cm
3.3			$z_e = 10\text{-}11$ cm	$z_e = 13\text{-}15$ cm
5			$z_e = 8\text{-}10$ cm	$z_e = 10\text{-}12$ cm
1	0.26-0.36	102-192	$z_e = 16\text{-}19$ cm	$z_e = 20\text{-}24$ cm
3.3			$z_e = 8\text{-}9$ cm	$z_e = 10\text{-}12$ cm
5			$z_e = 7\text{-}8$ cm	$z_e = 8\text{-}10$ cm

Fig. 2.

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Table 3. Nitrate photolysis rates

Depth	$j$ ( $10^{-7} \text{ s}^{-1}$ ), Qiu et al. [2002]	$j$ ( $10^{-7} \text{ s}^{-1}$ ), our parameterization
0	16	14
4	15	11
4	9	10
6	7	9.1
9	6.5	7.5
12	5	6.3
15	7	5.7
20	3	4.1
25	2	2.8

Fig. 3.

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Table 4: Comparison of snowpack actinic flux profile for Summit, Greenland using our parameterization and a Monte-Carlo radiative transfer model [Peterson et al., 2002] for homogeneous snowpack with  $\rho_{\text{snow}} = 340 \text{ kg m}^{-3}$ , snow grain diameter = 0.25 mm,  $C_{\text{BC}} = 0 \text{ ng g}^{-1}$ , and diffuse sky conditions.

Depth (mm)	290 nm (Monte-Carlo)	290 nm (this work)	350 nm (Monte-Carlo)	350 nm (this work)	390 nm (Monte-Carlo)	390 nm (this work)
0	1	1	1	1	1	1
5	0.94	0.97	0.95	0.97	0.96	0.98
10	0.91	0.94	0.92	0.94	0.93	0.94
20	0.85	0.88	0.92	0.88	0.93	0.89
40	0.74	0.75	0.79	0.77	0.82	0.78
60	0.65	0.65	0.71	0.67	0.75	0.69
80	0.57	0.56	0.63	0.59	0.68	0.61
100	0.50	0.49	0.58	0.52	0.64	0.53
150	0.36	0.34	0.44	0.37	0.50	0.39
200	0.25	0.23	0.32	0.27	0.37	0.28

Fig. 4.

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Table 5: Comparison of snowpack actinic flux profile for Summit, Greenland using our parameterization and a Monte-Carlo radiative transfer model [Peterson et al., 2002] for stratified snowpack with  $\rho_{\text{snow}}$  ranging from 260–390 kg m<sup>-3</sup>, snow grain diameter ranging from 0.15–0.30 mm,  $C_{\text{BC}} = 0 \text{ ng g}^{-1}$ , and diffuse sky conditions.

Depth (mm)	290 nm (Monte-Carlo)	290 nm (this work)	350 nm (Monte-Carlo)	350 nm (this work)	390 nm (Monte-Carlo)	390 nm (this work)
0	1	1	1	1	1	1
5	0.94	0.95	0.95	0.96	0.96	0.96
10	0.91	0.90	0.92	0.90	0.93	0.91
20	0.85	0.87	0.92	0.88	0.93	0.89
40	0.74	0.75	0.79	0.77	0.82	0.78
60	0.65	0.65	0.71	0.67	0.75	0.69
80	0.57	0.56	0.63	0.59	0.68	0.61
100	0.50	0.49	0.58	0.52	0.64	0.53
150	0.36	0.34	0.44	0.37	0.50	0.39
200	0.25	0.23	0.32	0.29	0.37	0.28

Fig. 5.

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