We are grateful to the editor's comments. Below we list detailed responses to the editors' comments. The comments are listed in italics, followed by the response in normal font with changes highlighted in blue.

Response to Editor's comments

Comments

Thank you for this extensively revised version. The main issue was in fact the comments by Dr. Hastings. While there is clearly room for further discussion, I believe that you have adequately addressed the reviewers' comments as well as Dr. Hastings' ones. I think your work represents a valuable contribution to this active research field. You have explained the scopes and limits of your model with more clarity and also given more detail on Dr. Hastings' work. This will probably help the reader forge his/her own opinion on the respective merit of each group's contributions. I am therefore pleased to accept your paper for publication in The Cryosphere, after you have addressed the minor points below. One of these points is on your calculation of snow specific surface area (SSA). In a way, I perhaps should have pointed that out sooner. However, I was in a position of conflict of interest, since your SSA calculations involves my own work, and Editors are in principle not supposed to promote their own work when editing papers, for obvious ethical reasons. However, if you agree that my comment is in the interest of the quality of your paper, I let you think about it. Obviously if you do so, you will cite (Carmagnola et al., 2013), of which I am the second author, and if you think this is self-serving, please just skip this comment.

Response: Thanks for the comments. The Carmagnola et al. (2013) has been cited in our previous version manuscript for the reported dust concentration within. We agree that the measured SSA at Summit in this work provides extra constrains for calculating the radiative transfer in our model and we are pleasant to add some discussions about it. Please see our detailed response below.

Comments

Line 52: why an error margin for d15N and not for d18O?

Response: This is because for δ^{15}N the value used here is adopted from the laboratory experiment results under Dome C conditions with error margin (Berhanu et al., 2014). While Berhanu et al. (2014) observed clear isotope fractionation for δ^{15}N during the photolysis experiments, they didn't find systematic change in δ^{18}O, so we used the theoretical photolysis fractionation factor for δ^{18}O from Frey et al. (2009) as the representative, which was derived with DC actinic flux conditions and different cross sections for ^{18}O-substituted NO_3^- isotopologues and no error margin reported.

Comments

Line 178. I just realized that your SSA values used to calculate your e-folding depth for actinic flux used equation (3) of (Domine et al., 2007). However, that equation may not be the most appropriate. First, the work of (Domine et al., 2007) is for seasonal snow, which may be different from snow at Summit. Second, you use equation (3) proposed for fresh snow, while there is not much fresh snow over the snow depth you consider. A better approach would have been to consider snow type as well as snow density, and use the most adequate equation. In any case, given the snow types at Summit, equations (4), (5) or (8) would probably have been more appropriate. These would have yielded lower SSA values and a greater e-folding depth. Then, since these equations may in fact not apply perfectly to Summit, it would be possible to compare *the SSA values obtained with those found by (Carmagnola et al., 2013) at Summit in spring (see their Figure 8). If their density values are similar to yours, then their SSA values would probably be a better estimate than using equation (3) of Domine. Also please mention that that equation has units of cm2 kg-1 for SSA and g cm-3 for density. Your stated SSA values of 44 to 51 m2 kg-1 in any case appear quite high for Summit, as (Carmagnola et al., 2013) found most photic zone values in the range 20 to 40 m2 kg-1. At this stage, it may not be appropriate to change your SSA values, but you may at least want to briefly evaluate the impact of using lower SSA on the e-folding depth and on your overall results. You may conclude that measuring SSA values would be desirable, but that currently the lack of measurements and uncertainties in estimates may modulate your results by a given amount. Depending on the results, you may add or not SSA as a source of uncertainty in your conclusions, e.g. line 452.*

Response: we appreciate the editor for pointing out the limitation in our calculation of snowpack SSA that used in modelling radiative transfer in snow. There are several regression relationships between seasonal snowpack density and SSA summarized by Domine et al. (2007) according to snow groups, namely fresh snow (type F), recent snow (type R) and aged snow (type A). The reason that we have chosen equation (3) to get SSA according to our measured snow density profile is because it yielded an e-folding depth of 12.3 cm at 305 nm wavelength that is close to the measured values (11.6 ± 2.6 cm) by Galbavy et al. (2007), despite the predicted SSA was higher than the values reported by Carmagnola et al. (2013). In comparison when using either equitation (5) or (8) that are for aged snow which yielded SSA values (4-20 m^2 kg^{-1}) that are significantly lower than the values reported by Carmagnola et al. (2013), and the resulting e-folding depth (i.e., 20.6 cm and 36.0 cm, respectively) are too high compared to the measured values (attached figure 1). While using equation 4 yield SSA values of 19 to 27 m^2 kg^{-1} and the corresponding e-folding depth of 18.0 cm, still much higher than the observed values by Galbavy et al. (2007).

The mean snow density reported by Carmagnola et al. (2013) was 330 kg m^{-3} in the top 50 cm, much lower than our snowpack (395 kg m^{-3}). In addition, the black carbon content measured in Carmagnola et al. (2013) (0.3 ng g^{-1} in average) is also relatively low comparing to the value used in this study (1.4 ng g^{-1}, according to Zatko et al., 2013). We acknowledge all these differences would introduce differences in the modeled e-folding depth, and it is probably the choosing of Eq(3) compensated other uncertainties, resulting in an e-folding depth that best matches the observations.

In order to remind the readers the uncertainties regarding the calculation of snow radiative transfer, in the revised manuscript we have made changes as follows:

Line 172: "we used the regression relationship between SSA and ρ_{snow} (SSA = −174.13 × ln(ρ_{snow}) + 306.4, in unit of cm^2 g^{-1} for SSA and g cm^{-3} for density, respectively) from Domine et al. (2007) to calculate SSA."

Line 179-187: "This likely explains why our calculated e-folding depth was smaller than Zatko et al. (2013) despite using the same impurity content. Note the regression relationship between SSA and ρ_{snow} from Domine et al. (2007) was for fresh snow, which may not be suitable for SSA prediction for the whole snowpack. However, using this equation yielded an e-folding depth that is similar to the observations by Galbavy et al. (2007), despite the yielded SSA appears to be larger than the observed values (20 to 40 m^2 kg^{-1}) by Carmagnola et al. (2013) for a Summit snowpack which has a much lower snow density (averaged 330 kg m^{-3} in the top 50 cm) than ours (averaged 395 kg m^{-3}). Nevertheless, given the uncertainties related to the calculation of snow radiative transfer that are currently not well constrained, the regression relationship between SSA and ρ_{snow} used here yielded a reasonable e-folding depth similar to the observations. Improvements can be made if snow physicochemical properties (e.g., SSA, density, and impurities concentrations) can be precisely well constrained by future observations."

Line 451: "Despite uncertainties in the model, e.g., specific surface area, quantum yield of snow nitrate photolysis, the export fraction, the modeled loss/redistribution of nitrate after deposition is consistent with previous studies, and explains the observed difference between $\delta^{15}N(NO_3^-)$ in surface snow and snow at depth."

Line 471-473: "On the other hand, precise measurements of snowpack properties, e.g., specific surface area, impurity concentrations, observational constraints on the quantum yield of snow nitrate photolysis, and better constraints on the export fraction are also needed in order to improve the model's performance."

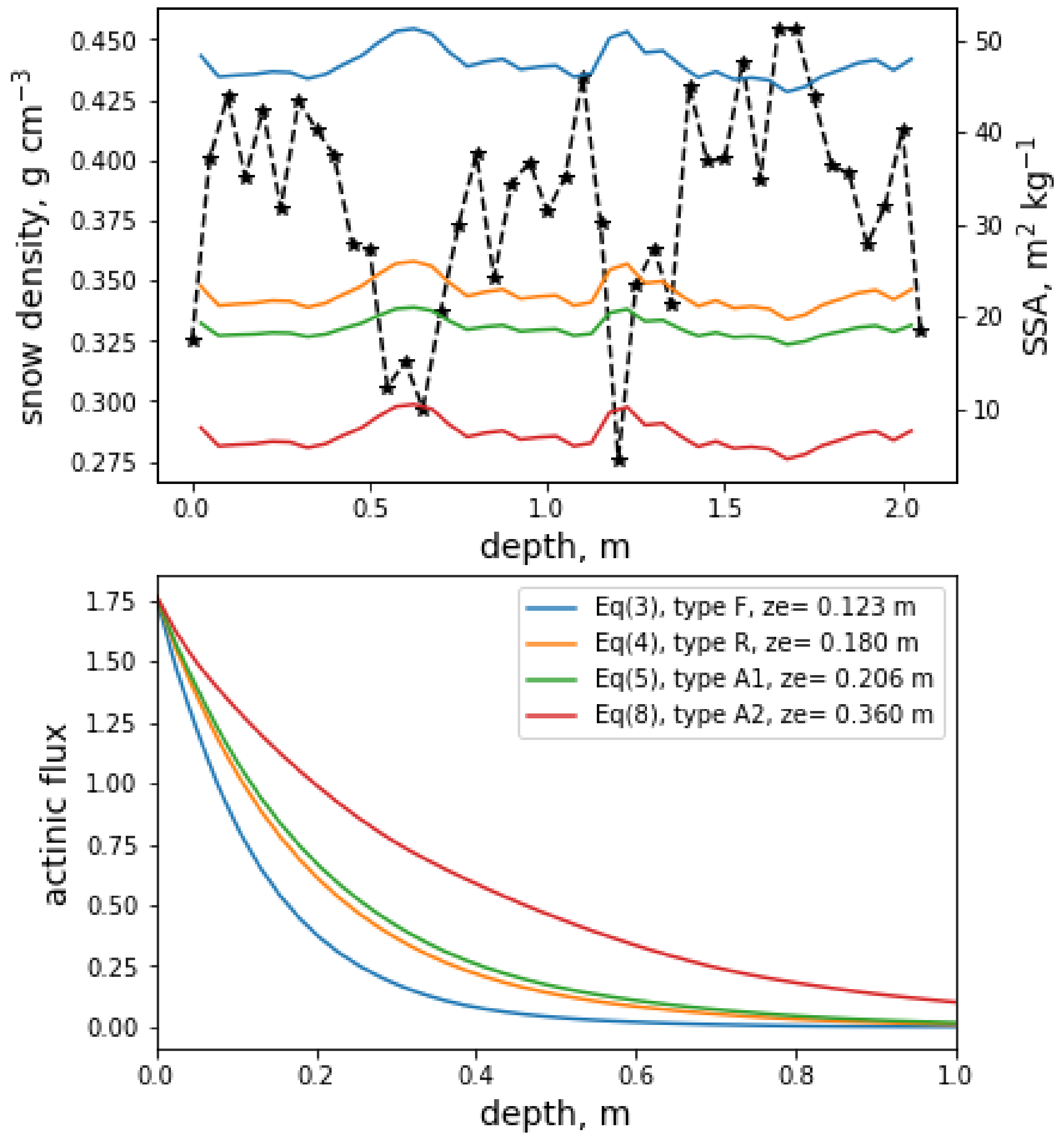

Figure1. Top: measured snowpack density profiles in Geng et al. (2014) and the calculated SSA according to the SSA-density regression relationships from Domine et al. (2007). Black: density; other lines indicate SSA using different regression relationships. Bottom: modelled snow actinic flux profile at 305 nm using different SSA-density regression relationships. The calculated e-folding depth is shown in the legend. Type F: fresh snow; type R: recent snow; type A: aged snow (Domine et al., 2007).

Comments

Line 464. "Overall, the model results suggest an important (if not dominant) role of post-depositional processing". By "if not dominant", do you mean "although not dominant" or "perhaps even dominant"? Please clarify.

Response: We meant "perhaps even dominant" here because the modeled magnitude of seasonal $\delta^{15}N(NO_3^-)$ difference is ~17.5 ‰ (without involving changes in $\delta^{15}N$ of F_{pri}) that is similar to the observations (16.1 ± 3.6) ‰ seasonality. We change the phrase in line 462 as follows:

"Overall, the model results suggest an important, perhaps even dominant role of post-depositional processing in regulating the snowpack $\delta^{15}N(NO_3^-)$ seasonality at Summit".

Reference

Berhanu, T. A., Meusinger, C., Erbland, J., Jost, R., Bhattacharya, S., Johnson, M. S., & Savarino, J.: Laboratory study of nitrate photolysis in Antarctic snow. II. Isotopic effects and wavelength dependence, J. Chem. Phys., 140, 244306, https://doi.org/10.1063/1.4882899, 2014.

Carmagnola, C., Domine, F., Dumont, M., Wright, P., Strellis, B., et al.: Snow spectral albedo at Summit, Greenland: measurements and numerical simulations based on physical and chemical properties of the snowpack, The Cryosphere., 7, 1139-1160, https://doi.org/10.5194/tc-7-1139-2013, 2013.

Domine, F., Taillandier, A. S., & Simpson, W. R.: A parameterization of the specific surface area of seasonal snow for field use and for models of snowpack evolution, J. Geophys. Res. Earth Surf., 112, F02031, https://doi.org/10.1029/2006JF000512, 2007.

Frey, M. M., Savarino, J., Morin, S., Erbland, J., & Martins, J.: Photolysis imprint in the nitrate stable isotope signal in snow and atmosphere of East Antarctica and implications for reactive nitrogen cycling, Atmos. Chem. Phys., 9, 8681-8696, https://doi.org/10.5194/acp-9-8681-2009, 2009.

Galbavy, E. S., Anastasio, C., Lefer, B. L., & Hall, S. R.: Light penetration in the snowpack at Summit, Greenland: Part 1: Nitrite and hydrogen peroxide photolysis, Atmos. Environ, 41, 5077-5090, https://doi.org/10.1016/j.atmosenv.2006.04.072, 2007.

Geng, L., Cole-Dai, J., Alexander, B., Erbland, J., Savarino, J., et al.: On the origin of the occasional spring nitrate peak in Greenland snow, Atmos. Chem. Phys., 14, 13361-13376, https://doi.org/10.5194/acp-14-13361-2014, 2014.

Zatko, M. C., Grenfell, T. C., Alexander, B., Doherty, S. J., Thomas, J. L., & Yang, X.: The influence of snow grain size and impurities on the vertical profiles of actinic flux and associated NO_x emissions on the Antarctic and Greenland ice sheets, Atmos. Chem. Phys., 13, 3547-3567, https://doi.org/10.5194/acp-13-3547-2013, 2013.