Answer to Teruo Aoki (Referee):

This paper describes the result of laboratory experiment using X-ray tomography on movement of dust particles in dry snowpack under temperature gradient metamorphism and isothermal metamorphism conditions. The paper clearly shows the dust particles move downward in case of temperature gradient metamorphism, in which three types of motion mechanisms are confirmed. They also present the quantitative vertical speed of the movement depending on relative position of dust particles to the ice matrix and estimated the total possible displacement of the dust distribution over dry snow period in the arctic. The authors discuss the influence of motion of light absorbing particles (LAPs) under strong temperature gradient in the arctic snow and the potential impact of dust vertical distribution near the snow surface on the radiative properties.

The manuscript is well-written with the effective presentations including movies. This study gives new findings on the time evolution of vertical distribution of LAIs in snowpack which is valuable information to communities of snow microphysics and climate studies. I recommend this paper for publication in The Cryosphere after revising the following points:

We gratefully acknowledge Teruo Aoki for his profound analysis of our work and constructive feedback, which helped us to improve the paper. The reviewer initial comments are written in black, our answer in blue and the corrections in the paper are highlighted in red. The line numbers used in the answers correspond to those of the corrected paper version.

Specific comments:

p.2, L9-11: "Typically, the albedo decreases more when the mass of LAPs is concentrated in the first centimeter compared to the case when the mass is distributed over several centimeters (Dumont et al., 2014)." The effect of the vertical inhomogeneity of snow impurities was already investigated by Aoki et al. (2000), in which the same situation is represented.
We are sorry for this omission and thank the reviewer for this suggestion, which was added to the reference list (l. 11 p.2).

p.9, L12-13: "In addition, the dust velocity varies with particles size: smaller particles are slightly faster than the larger ones (Fig. A3)." Please describe the (possible) cause. This is because the smaller dust particles as well as BC are more important for the albedo reduction. We should understand this mechanism.
We agree that this phenomenon may have important implications for the resulting albedo and now mention it in the text. However, we feel that the presented data does not contain any clear evidence of the origin of the phenomenon. We now only speculate (l. 7-11, p. 11) that: "This trend with particle size is important since smaller particles have more impact for albedo reduction (Flanner et al., 2012). It can be speculated that this trend is due to the fact that large particles have a larger absolute surface connected to the ice, thus reducing the speed of ice sublimation below the particle. For movements of type 3, we also expect the smaller particles to move faster than the large ones. Indeed, their fall into the pore space might be stopped later by the ice matrix, compared to the fall of larger particles (see Fig. 1)."

p.11, L1ff and Figure 6:
(1) Figure 6 suggests possible albedo increase due to the downward displacement of dust particles near the snow surface. Water vapor sometimes sublimates to the atmosphere from snow surface, which enhances the concentration of LAPs at the topmost layer (Aoki et al., 2014). This is opposite effect for the albedo change discussed here. Please describe that motion of dust particles near the surface could be affected by the other factor such as sublimation from snow surface.
We fully agree with the reviewer. We now added this information in the text l. 1-3, p. 13: "Moreover, Aoki et al. (2014) showed that the sublimation of the snow surface to the atmosphere can enhance the concentration of LAPs at the topmost layer, which may counterbalance the optical impact of the observed downward movement" and in the perspectives l. 21-28, p. 13.

(2) Albedo reduction due to dust contamination in snow depends on size distribution of dust particles. If the authors assume it based on the dust particles used in this experiment (i.e., Mongolian sand), it would be larger than the common atmospheric dust (e. g., A mode radius of dust model "Mineral-transported" compiled by Hess et al. (1998) is 0.5 mum) and thus the estimated albedo reduction could be smaller than usual. Please indicate the size distribution parameters or single scattering parameters of dust particles employed here.

We used the mass absorption efficiency of mineral dust compiled by Caponi et al. (2017) and used the measurements obtained for sample "Lybia in the PM_2.5 size fractions" (Table 4, therein). This is now mentioned in the text l. 4-10, p. 12 as "We considered typical mass absorption efficiency of mineral dust as measured by Caponi et al. (2017) (sample Lybia PM_2.5 therein) for the mass fraction of dust particles of aerodynamic diameter lower than 2.5 microns. The simulated particles are thus smaller than the one followed with the tomographic images. This choice was made to be consistent with the common atmospheric dust found in snow, e.g. Hess et al. (1998). The impact on albedo simulated here will also vary significantly for other types of dust with different chemical composition (e.g. Table 4 in Caponi et al. 2017). "

(3) When upper part of snowpack is heated by solar radiation in daytime, the temperature gradient would be inverse near the surface (Pinzer and Schneebeli, 2009). In that case the vertical movement speed of dust particles due to temperature gradient metamorphism may differ from the result presented in this paper (e. g., the speed slows down?). Please mention on this situation briefly.

Measurements in Greenland and in alpine snowpacks have effectively shown that daily cycles of radiative heating and cooling may lead to an inversion of the temperature gradient in the topmost 20 cm. However, in arctic snowpacks, daily variations of temperature near the surface are less pronounced (Pinzer and Schneebeli, 2009). Pinzer and Schneebeli (2009) used temperature on the order of 100 K/m and observed large volumetric turnover of up to 60% of the ice mass in one half-cycle. In such a case, we would expect the observed motion to be of the same order as observed in this study since a large amount of the ice next to particles would sublimate and set the particles free into the pore space. With lower gradient magnitude, the particles motion may slow down with time since it tends to be always the "same ice" (the ice envelop below and above the grain static part), which is active (sublimates/condensates) and ends to be clean. This situation is now briefly mentioned in the perspectives as future work to be done:

"The observation of the motion of LAPs in snow is based on only one experiment of each temperature regime (isothermal and steady state temperature gradient), using mineral dust (Mongolian sand) and snow samples confined between two ice lenses. Further experimental testing would help to confirm the presented results but also to assess the impact of the temperature gradient regime (e.g. mean temperature, gradient magnitude, alternating sign) and initial snow microstructure on the dust speed. In addition, it would be interesting to study (1) whether the chemical composition and size of the LAPs impact the observed motion (e.g. for BC), (2) whether temperature gradient metamorphism on longer periods could lead to complete snow cleaning (Doherty et al., 2010) and (3) whether the observed motion can be counter-balanced by snow sublimation into the atmosphere which tends to concentrate dust at the snow surface (Aoki et al., 2014)."

Figures 5-6 and A2-3: Some label values of both X and Y-axes are unreadable characters.

We do not see this problem on our web browser with the online version. We will carefully check it with TC editing service.

References(only new ones):

Aoki, T., T. Aoki, M. Fukabori, A. Hachikubo, Y. Tachibana, and F. Nishio (2000), Effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface, J. Geophys. Res., 105(D8), 10,219–10,236, doi:10.1029/1999JD901122.

Aoki, T., Matoba, S., Yamaguchi, S., Tanikawa, T., Niwano, M., Kuchiki, K., Adachi, K., Uetake, J., Motoyama, H., and Hori, M., (2014), Light-absorbing snow impurity concentrations measured on Northwest Greenland ice sheet in 2011 and 2012, Bull. Glaciol. Res., 32, 21–31, doi:10.5331/bgr.32.21.

Hess, M., P. Koepke, and I. Schult, (1998), Optical properties of aerosols and clouds: The software package OPAC, Bull. Am. Meteorol. Soc., 79, 831-844, doi:10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2.

Pinzer, B. R., and M. Schneebeli (2009), Snow metamorphism under alternating temperature gradients: Morphology and recrystallization in surface snow, Geophys. Res. Lett., 36, L23503, doi:10.1029/2009GL039618

Flanner, M. G., Liu, X., Zhou, C., Penner, J. E., and Jiao, C.: Enhanced solar energy absorption by internally-mixed black carbon in snow grains, Atmos. Chem. Phys., 12, 4699-4721, https://doi.org/10.5194/acp-12-4699-2012, 2012.