

## ***Interactive comment on “Physically based summer temperature reconstruction from ice layers in ice cores” by Koji Fujita et al.***

**Koji Fujita et al.**

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Dear Elizabeth Thomas as Reviewer #2

Thank you for your comments on our manuscript submitted to CP.

[reviewer comment] Ice cores have long been used to reconstruct past surface temperatures, however in areas of surface melting this is not always possible. This paper presents a new method for reconstructing summer temperatures from melt layers in ice cores. The new method, based on an energy balance model, provides a valuable alternative to traditional surface temperature proxies, however the potential limitation is that melt must be present.

[author reply] Thanks for the positive evaluation.

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[reviewer comment] General comments: I found the term “ice layer” confusing. What you are referring to is “melt layers” or even “ice lenses” that occur in the firn.

[author reply] We changed the term to “melt layers” including the title.

[reviewer comment] Line 127. I am unsure of the assumption “water refreezing alters the snow density up to the ice density ( $\rho_i$ ,  $900 \text{ kg m}^{-3}$ ), but does not prevent the water percolation”. Can the water percolate through the ice layers? One of my concerns with the method is that melt layers act as a barrier for further melt percolation. Thus what might appear to be a large melt layer could be comprised of several smaller melt events. In this case you would over estimate your summer temperature reconstruction. This is also a drawback of using the annual ice layer thickness (line 194). Is the assumption therefore that the melt occurs in a single event each summer?

[author reply] Modeling percolation of large amount of meltwater is a challenging issue and we have no idea how to improve the present scheme of this study. If we have a scheme expressing that a melt layer prevents meltwater penetration, however, the reconstructed SMT would be “under estimated” because thicker layer would be formed than that by the present scheme under the same temperature condition. If multi melt layers are identified in an annual layer, we assume a single melt layer thickness by summing up thickness of those layers. This issue would cause large SMT errors especially for the period during which thick melt layers are found (orange bars in Fig. 7). We will add these descriptions in the discussion section.

[reviewer comment] I think you need more information about the ice core data used. Either in the text description or in table 1. How were the ice cores dated? What is the approximate dating uncertainty? Are your years from summer to summer or winter to winter? How was the ice layer thickness determined? Visual? Line scanner? How accurate are these measurements? Can you determine small melt layer or just large melt events? Is it possible to identify multiple smaller melt events? Can you identify melt layers at depth or is it only possible in the firn?

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[author reply] We will add dating method, age markers, dating error, and method for melt layer measurement in Table 1. Annual layer of three ice-cores are defined between winters while the SE-Dome ice-core is dated in monthly scale. The minimum melt layer thickness and its accuracy are  $1 \pm 1$  mm in all ice cores. If multi melt layers are identified in an annual layer, we assume a single melt layer thickness by summing up thickness of those layers. We will add these descriptions in Sect. 2.5. We only dealt with melt layers in the firn in this study, and the identification of melt layer at depth of ice is out of focus of this study. We will add a brief description about this issue in the discussion section.

[reviewer comment] I am not sure if there is a better term for "look-up tables" but I found the term strange. Would calibration tables be better?

[author reply] "Calibration table" sounds strange for us because we do not calibrate any results through the tables. Once we create a table, we can retrieve a value of the target variable (SMT: summer mean temperature in this study) from a combination of explanatory variables (annual accumulation and refreezing amount in this study). We think that this should be called "lookup tables".

[reviewer comment] How well does ERA-interim capture conditions at the ice core sites? Have there been any studies to demonstrate this? My concern is that the approach is heavily dependent on the reanalysis data, but for many ice core sites (especially those subject to melt) the spatial resolution of ERA-interim may not be suitable. Is there a way you can demonstrate that ERA-interim is suitable?

[author reply] We do not think that there are studies confirming the validity of reanalysis datasets (not only ERA-Interim but also ERA5, NCEPs, MERRA and others) at an ice core site where observational data is generally unavailable. Validity of ERA-Interim air temperature has been tested with several observational data in the high mountain Asia (Sakai et al., 2015) though they are not located at high-elevation ice core site but around glacier termini. On the other hand, representativeness of those datasets does

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not matter in this study because air temperature and precipitation are systematically modified to obtain "lookup table". Our sensitivity tests show that the annual temperature range only affects the estimated SMT. This suggests that the reanalysis data would be suitable for demonstrating this study if the annual temperature range was reliable at the ice core sites even though the representativeness of temperature and precipitation amount were not precise. We will add some descriptions about this in the revised manuscript. Other effective parameters are precipitation and firn albedo. But precipitation is a given parameter from ice core and issue of firn albedo (and albedo scheme improvement) is already addressed in the original manuscript.

[reviewer comment] I think the issue of impurities in the ice could be a limitation to this method. The authors include a caveat in the discussion that the albedo scheme needs improving. I think this is especially important for coastal or continental sites, which may be subject to local dust sources. The surface mass-balance model by Goelles and Boggild includes a dynamic ice albedo component. In addition to dust and black carbon, this model includes clouds and the angle of the sun. GOELLES, T., & BØGGILD, C. (2017). Albedo reduction of ice caused by dust and black carbon accumulation: A model applied to the K-transect, West Greenland. *Journal of Glaciology*, 63(242), 1063-1076. doi:10.1017/jog.2017.74

[author reply] The issue of impurities has been already addressed at L352-355 of the original manuscript. The study provided here (Goelles and Bøggild, 2017) mainly deals with albedo and melting processes in the ablation zone while our study focuses on that in the accumulation zone. In addition, as we have addressed in the original manuscript, our studies have revealed that "deposition timing of impurities" is much more important than albedo schemes. We admit that our albedo scheme is not sophisticated but we do not think that the study by Goelles and Bøggild (2017) is appropriate to be cited for discussing the issue and impact of impurities.

[reviewer comment] I think a new method of reconstructing temperature that is not reliant on stable water isotopes is important. However, stable water isotopes are a

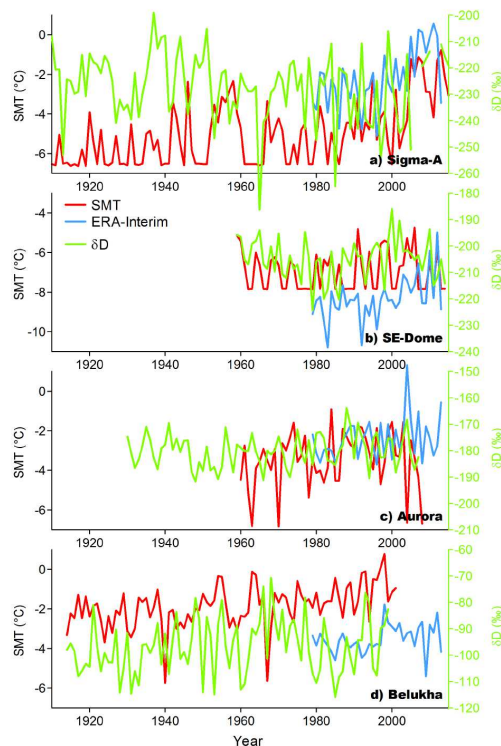
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well-established method. I wonder if it would strengthen your case to include the stable water isotopes for these ice cores in your figures (Fig. 7), or a supplementary figure, to demonstrate the imperfect nature of the stable water isotopes – temperature relationship. I found the correlation between SMT and ERA-interim convincing but clearly it is not an exact match. However, if you presented the stable water isotopes you would also expect differences. Is the SMT reconstruction from stable water isotopes better or worse than your method? Is it even possible to get a summer mean temperature from isotopes? I think you should include some additional background in the introduction about the drawbacks of other temperature reconstructions and how the information can be lost in the presence of surface melt. Future climate warming means we need additional methods of extracting climate information from ice cores that may be subject to melt.

[author reply] We compare our SMT and deuterium stable water isotope (SWI). Figure 1, which will be shown as a supplementary figure in the revised manuscript, shows that inter-annual variabilities of deuterium are different site by site; large at the Sigma-A and Belukha sites while small at the SE-Dome and Aurora sites. In addition, fluctuation and trend of SWI are different from those of SMT at the same site. This is probably because the annual SWI signal is affected by winter accumulation and seasonal variability of precipitation. In addition, the SWI approach requires observational temperature data to convert SWI to temperature, which is the same issue in the empirical approach using melt layers. We will add descriptions about this comparison in the discussion section of the revised manuscript. We add two colleagues by contributing these isotope data.

Interactive comment on Clim. Past Discuss., <https://doi.org/10.5194/cp-2019-97>, 2019.

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**Fig. 1.** Reconstructed (red lines) and ERA-Interim (light blue) summer mean temperature (SMT, left axes), and deuterium water stable isotope of ice core (light green, right axes)

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