Review 2

<u>Introduction</u>

The preprint 2023-1939 by Moser et al fills a current gap in the literature on the physics and chemistry of ice in the perspective of retaining climatic and environmental information out from coring ice fields that temporarily are effect by melt. Standard textbooks such as Takeo Hondoh´s book "Physics of Ice Core record" from 2000 are usually focused in cold firn ice cores (melting phenomena are mentioned in Hondoh´s book, and maybe worth a reference in this manuscript!), and the development of firn modeling and analytical technologies have opened new lanes of possibilities in extracting interesting and important information out from periodically melting / warm firn ice fields. This preprint is a result of a large, brave and commendable effort to collect and present a benchmark of where this field of science is today. With the current warming and its accelerated effect, it is of interest to retrieve information from these ice fields before the information gets to washed out by percolating melt and rain water. This work can such play an important role as a standard piece for new and old students in this field.

<u>General comments</u>

Since this is a review article I will focus at the organization of this work. My first reading of the preprint made me somewhat confused of where the review was aiming at. The general organization: 1 Introduction; 2 From melting to melt-affected ice cores; 3 Manifestations of melt in ice-core records; 4 Current applications of melt layers as proxies; 5 Conclusions and outlook makes sense from 1 to 3. Section 4 hang a bit outside the general structure, and could be added into section 3, or even placed into 2.3.1. Maybe assess the general organization again. The illustrations are another topic that caught my eye. Potentially there could be hundreds of illustrations, since the review cites a large amount of work. From what I can see the figures are used to illustrate important principles and key information in the review. The illustrations are perhaps also used to break to long sections of text, into more color and different texture to please the readers eye. If so, pages 6 -12 are lacking illustrations, and such are a bit more dense and "heavy" to get through. Try to anchor the figures better in the text; to take the opportunity to explain the information in figures and expand the relevance of the figures in the section. With this, the illustrations will bring in more information and will be used as to bring in additional knowledge, apart from the aesthetical value.

Dear Veijo Pohjola,

We appreciate the time and effort that you dedicated to providing feedback on our manuscript and are grateful for your valuable comments to our paper. We have incorporated most of the suggestions, and they are both highlighted within the manuscript and explained in a point-by-point response below.

Regarding the general organization of the paper, we agree with your assessment that Sect. 4 on current applications of melt layers as proxies received special emphasis in comparison to the second-order sections on melt structure, chemistry, isotopes and gases (Sect. 3.1.-3.4.) by making it a first-level chapter. Following your advice, we have placed former Sect. 4 at the end of Sect. 3. Now numbered Sect. 3.5. in the 'Manifestations of melt in ice-core records' chapter, it is more obvious that melt features can be considered as environmental proxy in a similar way as the ones discussed in Sect.3.1.-3.4.. At the same time, keeping this content at the end of Sect. 3 maintains our train of thought from melt formation to manifestations and interpretation, which we hope is intuitively chronological from a researching point of view and thereby eases the reading experience.

As you say, we focus on providing illustrations of important principles. Since melt effects on chemistry have historically been more under debate than the effects on stable water isotope (SWI), the authors have intentionally dedicated a few figures to clarifying the related aspects. The preservation issues and factors relevant for SWI as known to date are partly covered in Fig.7, so that have added a direct reference to it in line 585 of the revised manuscript. Figure 5 further shows an exemplary melt-affected yet seasonally resolved SWI record from the Swiss Grenzgletscher, which we reference in line 597 of the revised manuscript. Beyond these two figures, the authors see no need for a separate illustration.

To spread the illustrations more evenly within the manuscript, we have moved some of the figures (Fig. 1, Fig. 2), within their respective section. To ensure closer ties between text body and illustrations, we have further added references to Fig.1 in line 274 and line 336 of the revised manuscript. In line 728, we now refer to Fig. 3 to re-emphasize the diversity of melt imprints. In addition, Figure 3 has been repositioned to revised line 386, so that the direct link between the sentence above and the figure is clearer. As the figure caption contains significant level of detail and is well-embedded in the reading flow, we think that a repetition of this content in the text body is not necessary. A reference to Fig. 4 has been added in line 427 of the revised manuscript. Another reference to Fig. 6 has been added in line 524 of the revised manuscript, and aside from that, it is already explained in detail in line 449-454 of the revised manuscript. While the paragraphs in lines 461-504 are already aligned with the content and structure of Fig. 7 (right 1-3), we have added more detailed references to the right part of the illustration in the respective sub-sections of the text body: (1) in line 470, (2) in line 476 and 490, (3) in line 497.

<u>Further comments:</u>

1. How is the structure are lined up in the abstract as compared in the introduction, and further connected to the different sections. First, should the seven points in the abstract represent the different sections, and such display a “table of content”? Second, should these items of content be similar in the abstract and in the rows 90-95 in the introduction?

Thank you for pointing out potential confusion about the numbering in abstract, introduction and manuscript sections. For clarification of the content given at the end of the introduction, we have aligned the numbering in line 111-115 with the section numbering. It now reads: “This paper provides a detailed literature review regarding external drivers of melt events (Sect. 2.1); physics of melt layer formation and behaviour during snow metamorphism (Sect. 2.2); identification and quantification of melt (Sect. 2.3); structural characteristics of melt features (Sect. 3.1); effects of melting on records of chemical impurities, i.e. major ions, trace elements, black carbon (BC), and organic species (Sect. 3.2), stable water isotopic signatures (Sect. 3.3), and gas record (Sect. 3.4); applications of melt layers as environmental proxies (Sect. 3.5).

The content structure in the abstract (line 15-18) is generally linked to the section structure of the paper in order to show the main outline, but it does not strictly copy the sequence of section titles to avoid losing track of the main topics by listing all sub-chapters and section numbers in the abstract. We keep this more detailed information for the introduction of the paper itself and have removed the numbers in the abstract to prevent confusion. Revised line 15-19 now read: “This review first covers melt layer formation, identification and quantification of melt, and structural characteristics of melt features. Subsequently, it discusses effects of melting on records of chemical impurities, i.e. major ions, trace elements, black carbon, and organic species, as well as stable water isotopic signatures, gas record, and applications of melt layers as environmental proxies.”

2. Could you consider to walk the reader through the arguments for the chosen organization of the manuscript after your presentation of aims and objectives?

To explain the train of thought underlying the paper while maintaining brevity of this introduction, we have added the following clause in line 115-117: "Here, we review formation, manifestation, and interpretation of melt chronologically and focus on those aspects of near-surface melting, which are important for ice-core research."

3. The ice chemistry section could be separated between particulate and ionized content. The analytic methods and the information out of these parameters are quite different, and they also bring different information, and behave differently during wet events.

Thank you for this comment. Unfortunately, it is not always the case that different methods are used for particulate or ionic species, so that the existing literature only allows for an integrated discussion of the elution behaviour of various chemical species. In the case of trace elements analysed with ICP-MS, for example, everything from fully soluble (ionic) species to insoluble (particulate) species is measured. On the other hand, ion chromatography only assesses the ionized chemical content. While a more comprehensive analysis and discussion of elution behaviour of individual species in their various states is of interest, this requires a lot more research beyond the current state of literature and therefore is beyond the scope of this paper. Nevertheless, we agree that general differences in elution behaviour of particulate and water-soluble chemical impurities need to be mentioned, and our paper explicitly addresses them in Fig. 6 and the corresponding text body (revised line 444-455). Towards the end of Sect. 3.2 (line 550-566), we also lay out how various chemical species, which differ in characteristics and contained environmental information, can be used in the light of differing elution behaviour.

4. The section of water isotopes is fairly short in comparison to the chemistry section. You could argue that the basic information is available in a number of texts, and refer to more basic literature of this sort, perhaps begin with the pioneering work by Dansgaard.

Indeed, extensive publications on the general potential of stable water isotopes for ice core climate reconstruction have been published elsewhere, so that we only discuss alterations of SWI through melting and refreezing here. We refrain from adding many introductory literature references, which are not crucial for understanding here, but have amended the start of the SWI section (Sect. 3.3.) to keep the broader picture in mind. Revised line 574-578 now reads: "Isotopic fractionation is fundamental to the interpretation of stable water isotopes (SWI, Gat, 1996) as climate proxies in ice cores, and an extensive body of ice-core scientific literature starting with the pioneering work by Dansgaard (1964) exists on this topic. Here, we solely discuss alterations of SWI through melting and refreezing, because the fractionation of heavier and lighter isotopes takes place during phase changes, so that melting and refreezing in the snowpack plays a significant role (Koerner et al., 1973)"

Minor comments

Li 12-14. Rephrase the sentence "Since coastal…..in alpine settings".

From your recommendation to rephrase the sentence, we understand that our use of the terms "coastal low-elevation", "(sub-)polar" and "alpine" has been confusing here. This second sentence of the abstract is intended to briefly highlight that melt effects are an increasingly important issue for sub-/polar researchers, who are probably the main readership of this paper (revised line 15-16). In addition, it is important to the authors to indirectly acknowledge the longer-standing expertise of alpine ice core researchers in working with melt-affected ice core records from warmer conditions. In *the hope that this explanation helps, we have changed the wording in line 12-14 slightly: "Since (sub-)polar ice caps are crucial environmental archives but highly sensitive to ongoing climate warming, the Arctic and Antarctic research community is increasingly faced with melt-affected ice cores, which are already common in alpine settings of the lower latitudes."*

Li 14. Does not this review also include warming firn outside alpine settings?

You are right. This review addresses the fundamental issues associated with melt-affected ice cores in a range of conditions. We mention alpine settings here, as alpine ice core research has had and found ways to deal with melt-affected ice cores, so that researchers who are less familiar with this topic, can learn from this. Furthermore, we expect sub-/polar researchers to be a key part of the readership of this paper, so that this part of the abstract points out the increasing relevance of melting in these regions. To cover both these aspects, the sentence in revised line 12-14 has been amended to: "Since (sub-)polar ice caps are crucial environmental archives but highly sensitive to ongoing climate warming, the Arctic and Antarctic research community is increasingly faced with melt-affected ice cores, which are already common in alpine settings of the lower latitudes."

Li 97. On this row there is a short aim and objective, that can be expanded as commented in major comments above, if we, has the meaning authors, that line is badly posed, since I would presume it is the reader who wants to learn…

Following your recommendation, we have amended the wording in line 111 of the revised manuscript to: "This paper provides a detailed review … ". In a similar way, we have changed revised line 118 of the revised manuscript to: "Finally, this study aims to learn from alpine ice-core scientists and contribute…"

Li 128-131. May the sentence of temperature increase related to heat content be too trivial in The Cryosphere?

We agree with your assessment and have shortened the paragraph to one amended sentence in line 138-139 of the revised manuscript: "Positive air temperatures are the primary, non-linearly related trigger of melt and a well-established, integrated proxy for melt intensity (Abram et al., 2013; Hock, 2003; Bell et al., 2018)."

Li 133-149. This section on heat from advected air masses over ice fields is a bit exhaustive, and takes focus off the ice properties. Consider to shorten/cut this part.

Thank you for this comment. We understand that this elaboration about meteorological factors for melt formation can seem less relevant in comparison to the structural and chemical assessment of melt-affected ice cores as presented in the following chapters. However, we see it as fundamental context for interpreting ice core records, which can be melt-affected by a variety of conditions. Given the close link of meteorology and the physics of melting (Sect.2.2.), cutting this part could take away from the basis of ice-core climate reconstruction. For this reason, we have removed one longer sentence in revised line 152 and otherwise kept the main elements of this section.

Li 184. Typo? "Therefor"

Thank you. The spelling in line 192 of the revised manuscript has been corrected to: "Therefore, modelling of melt…"

Li 635-639. I would guess that gas content and gas evacuation capacity is dependent on how the ice crystal boundaries are configured in ice matrix, and how the effective porosity varies in the firn/ice matrix.

The reviewer assumes correctly that the Total Air Content (TAC) depends, among other factors, on the pore space volume of the firn in the lock-in zone. If a melt feature is present in a given volume of firn in the lock-in zone, it will have less open pore space because of the volume occupied by solid ice instead of porous firn. This therefore leads to a lower TAC as described in revised lines 659-664 in the Gas Section. We have revised this section for improved clarity:

"Lastly, total air content (TAC) is often interpreted as driven by, among other effects, the elevation of the glacier surface, i.e. higher elevation is associated with lower TAC as the barometric air pressure decreases with altitude (Delmotte et al., 1999; Martinerie et al., 1992). However, a reduced TAC may also be indirectly caused by a melt feature because the presence of impermeable ice, i.e. the refrozen melt layer, has replaced porous firn and thereby lowered the volume of pore space in melt-affected firn in the lock-in zone. This may lead up to 40% reduction in TAC (Stauffer et al., 1985), even though this reduction does not seem to be consistent throughout different melt features and ice cores."

Note that the ice crystal boundary configuration beyond this point does not impact the TAC. This is because all available TAC measurement techniques extract 100% of the trapped air from the ice sample, independent of the ice crystal structure.