Reply to Anonymous Referee #1 comments on "Comparison of manual snow water equivalent measurements: questioning the reference for the true SWE value" by Maxime Beaudoin-Galaise and Sylvain Jutras, The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-354-RC1, 31 Dec 2021

On behalf of Sylvain Jutras, co-author, and myself, I thank the anonymous referee #1 for his comments on the submitted manuscript. Following the reading of his general and specific comments, responses to each comment have been formulated point-by-point. Reading these comments allowed us to identify concrete modifications to the manuscript, as mentioned in our replies. At the request of the publisher, it will be possible to provide the revised version of the manuscript.

Comments from the reviewer in blue
Answer in black

1. The main finding of the study is not new, already others (e.g. org/10.1002/hyp.13785) came to the same conclusion.

There are many similarities between our study and López-Moreno et al (2020) (DOI: 10.1002/hyp.13785). However, we think that our main finding is different from that brought by López-Moreno et al (2020). To defend our point, we will make a brief comparison between the two studies. The objectives of the article by Lopez-Moreno et al (2020) was to estimate the variability and errors of various snow tube sampler and to distinct the effect of the natural variability from the error due to the instruments and the observers. To do this, they compared nine snow samplers made of different materials and of different diameters (between 3.81 and 10 cm). Snow pits were made at their second study site to estimate snow density of the snowpack with density cutter measurements every 5 cm depth. In this study, the snow pits were used in the results and discussion as a description and confirmation of the homogeneity of the snowpack. The measurements made from the snow pit, therefore more particularly with the SnowMicroPen, confirmed the homogeneity of the snowpack in order to validate that the error and variability results are mainly due to the instrument and the observer for a site and a given time.

For our submitted manuscript, the objective was to estimate the uncertainty and measurement error of SWE estimation methods. More specifically, we compared the methods used in our study area, the boreal forest of Canada, but also elsewhere in the world. These methods are the snow samplers and the snow pit methods described. The snow pit was analyzed as a SWE measurement at the same scale as the three samplers used. The snow pit, according to the methodology employed in our study or by different protocols, is often used as the true SWE reference, but not exclusively, in the literature. Contrary to López-Moreno al (2020) and other previous studies, the snow pit was considered in the study as a method for estimating the SWE in the same way as the snow samplers. Although there are already published studies on the uncertainty and error of density cutters, we consider that this manuscript presents novelty by the comparison of the SWE estimation uncertainty between the snow pit and the snow samplers of different sizes. The results of uncertainty due to the instruments (Table 3) showed that the snow pit is a method with a high uncertainty, and therefore should not be used as a true SWE reference. This finding has not been documented in the literature according to our knowledge and it represents a novelty. Consequently, we disagree with the comment stating that the main finding of our study is not new. We do understand that our conclusions about the difference in variability between a small diameter sampler (federal sampler) and large diameter samplers (ULS and HQS) are similar to what was documented by López-Moreno et al (2020). Although the article by López-Moreno et al (2020) is already referenced in our manuscript, a reference has been added to the paragraph to the discussion section (section 4.2; lines 430-447) in order to validate these similar conclusions.

2. The authors question, already in the title, the reference for the true SWE by assuming the true SWE is the one undertaken with what they call the snow pit method.

It was not our intention to assume in our title that the snow pit was a reference for the true SWE. In the boreal biome, several measurement methods such as snow samplers can act as a reference for the true SWE. The intention of our title was to highlight our main objective which is to determine, between different manual SWE estimation methods, which is the most appropriate method to be used as a reference for true SWE. As mentioned in our introduction, the snow pit and the snow samplers are different methods used as a reference of the true SWE to validate manual sensors for example. We rather wanted to mention that when several measurements are taken, as for us in our study site or for an organization which wonders which instrument or method used, there is still a question about which is the best method. To our knowledge, we haven't found any publication using a SWE reference, whether it was a snow pit or a snow sampler, where a robust justification of the choice of the method was explained accordingly, based on its uncertainty and measurement error. The reference method is simply stated and used without any further consideration of its uncertainties. Even if the snow pit is often used by default as a reference for the true SWE in articles referring to SWE measurements in boreal and temperate ecosystems, we do not think this implies it in our title. Likewise, our introduction was not written in this sense.

The title was modified to avoid the misinterpretation of our intent (replacing "questioning" by "seeking") and to specify the location where the study is being conducted. This will avoid confusion due to geographical differences in the methods used for SWE estimation.

3. The snow pit method as it was used in this study uses a density cutter of 250 cm^3. As "prove" for their assumption they reference seven studies, of which only two also used similar-sized density cutters. The other studies did not specify a reference or the size of the cutter used or used a much larger cutter (up to 3500 cm^3).

The purpose of this paragraph in the introduction (lines 60-73) is to document the use of the snow pit as a reference for true SWE in the literature and the density measurement with the density cutter. The seven studies are cited (lines 60-64) to demonstrate that the snow pit has already been used in the literature as a manual SWE measurement reference to evaluate others SWE estimation methods (for a calculation of error for example). In order not to claim that these studies made snow pits with protocols similar to ours, a sentence has been added in this paragraph to clarify it that these studies use a variety of protocols and density cutters for the SWE estimation.

4. The volume of the cutter and also its usage horizontally (per layer) or vertically with a plate plays an important role. If used horizontally, as in the current study, the application in a continuous manner is crucial. Sentences like “density measurements were made in each contrasting snow layer that was thicker than 5 cm” leave the impression that these measurements were performed in a subjective manner, which can cause large errors (doi.org/10.5194/tc-10-371-2016) and could explain the partly contrasting results to earlier studies.

Clarifications have been made to the section 2.3 in order to better describe the method and the limits of sampling with the density cutter used. To clarify, the measurements with the density cutter were made for each stratigraphic layer of the snowpack, after a description and delimitation of each snow layer in the snow pit. In our study, we used a wedge cutter, since it is a frequently used tool for snow pit SWE measurements, but according to the method of stratigraphic sampling. The density cutter used has a dimension of 10 cm by 5 cm. The measurement with the density cutter was preferably done vertically, only for snow layer of thickness ≥ 10 cm. On the other hand, for snow layers with a thickness <10 cm and ≥5 cm, the measurement was made horizontally. Thank you for your comment and these clarifications have been added at the beginning of section 2.3. We had only described the type and the volume of the density cutter used, but this additional information appears to be relevant.

In reference to the article by Proksch et al (2016) (DOI: 10.5194/tc-10-371-2016), they used a cylinder cutter for a stratigraphic sampling, while the box and wedge cutters are used for a sampling at a constant vertical resolution. Although the cylinder cutter is the only one used in Proksch et al (2016) for the density measurement per snow layer, it is not inadvisable to use another type there. With a smaller diameter, the cylinder cutter is advantageous in order to allow the measurement of a thinner snow layer, but it is still possible, in our opinion, to estimate the density and the SWE per layer of a snow pit according to our method with a wedge cutter.

5. The authors use the same height (h) in their formula 1 und 2, which is definitely wrong as the height of the sampled core can always be different from the height of the snowpack. One reason that h in formula 1 & 2 is different is given in the study by the fact, that for the HQS “it is necessary to insert a plate in a slot at its base to prevent snow loss”, which implicates that not the entire height of the snow pack could be measured.

For formula 1, the reference used and cited (Kinar and Pomeroy, 2015) uses the snow depth for the density calculation. Snow depth is also used for formula 2 according to Pomeroy and Gray (1995). The study by Dixon and Boon (2012) also use the same height, i.e. the snow depth of the snow cover, to calculate the snow density and SWE from a snow tube sampler. This 2-step calculation assumes that the snow sample taken corresponds to the snow depth of the snowpack. If there is a difference between the length of the snow core and the snow depth of the snow cover, we assume that it is due to snow compaction in the tube during sampling. By manipulating the sampler, it is possible to have a compaction of the snow layers, and especially for the layer with lower density. When the sampler is inserted into the snow cover, contact with the ground or with ice or crust layers during its insertion can compact the snow inside the tube. This is a hypothesis brought into the discussion (line 390) to explain the lower snow core length / snow depth average ratio of the federal sampler (SFS). Since it is necessary to remove the SFS from the snow cover before being able to measure the snow core length, it involves additional handling compared to ULS and HQS which can lead to more compaction. Since the snow core cannot be seen when inserting the sampler into the snowpack, it is not possible to validate these hypotheses with our methods. As specified in the methodology at lines 162-166, care was taken to ensure that the samplers were sufficiently deep in the ground before removing the corer. It was possible to validate that the entire snowpack was sampled for a valid measurement. In order to avoid overestimating the snow depth, the measurement of the snow depth was noted when the observer perceived that the sampler was in contact with the ground. After the snow depth was noted, the sampler was pushed further into the ground to create a plug (SFS) or before digging down to the ground and doing the following steps (HQS and ULS). Your comment showed a misunderstanding of our protocol du to its lack of clarity, so modifications have been made to section 2.2 (lines 145-149).

6. Since the height of the snow pack, also in a perfect field like the one at NEIGE site, can spatially vary (due to radiation, wind or rain events) it is important to reference the measured density to a fixed snow height or to specify the uncertainty involved by the varying snow height.

Indeed, it would be interesting to document the variability of the snow depth during the measurements. As for SWE, the coefficient of variation (CV) of for each snow sampler were calculated for the snow depth and the snow density. With these new results, a new table was created with the coefficient of variation values of each snow samplers for snow depth, snow density and SWE. For the snow depth, the values are for the SFS, HQS and ULS respectively 2.82 %, 2.23 % and 2.01 %. For the snow density, the values are for the SFS, HQS and ULS respectively 5.16 %, 3.77 % and 3.99 %. the uncertainty CV (%) values in the first line of table 3 have been deleted, since they are been moved to this new table. This new table was numbered table 3, and the numbering of the following ones was shifted accordingly. To illustrate the spatial variability of mean snow depth on the NEIGE site, the average CV of the snow depth from the CV for each measurement day (all methods combined) was calculated. The NEIGE site shows a CV of 3.15 % (± 2.82%). This result has been added to a new subsection 3.1 at the beginning of the results section, discussed in detail at the reply to comment #7. Changes to subsection 2.4.1 (lines 218-222) have been made to describe these additional calculations in the section Material and methods.

7. There is no information given about the type of snowpack (e.g. typical stratification, mean density) or about the distribution of the measured snow heights.

Compared to similar studies, our data was not taken over a reduced number of days, but over 91 days over 4 years. These weekly measurements made during most of the winter cover a wide variety of conditions, such as during periods of snow accumulation or melting. Initially, we did not think of adding results on the stratification of snow pits, because it is mainly used for estimating the snow density per snow layer. In order to provide a better description of the study site in the results section, a new subsection has been added at the beginning of the results, i.e. section "3.1 Snow Measurements Distribution". The numbering of the other subsections has been shifted. Table 2 and related paragraph (lines 299-304) has been moved to this section. In response to this comment, a new figure with its description have been added following Table 2 and still in the new subsection 3.1. This figure illustrates with three histograms the distribution of the average values of snow depth, snow density and SWE for each measurement day. To avoid duplicating the same results, the average, minimum and maximum SWE values have been deleted from table 2. For each histogram, it has been included the mean value and its standard deviation for snow depth (99 cm ± 30 cm), snow density (0.298 g cm-3 ± 0.068 g cm-3) and SWE (281 mm ± 109 mm).

8. I'd recommend the authors to fully rewrite the study, to focus more on the new ULS snow sampler and to publish in another journal.

With all due respect, we believe that there was some misunderstanding between the objective of our article and what was interpreted by the reviewer. We fully understand these comments, and several modifications have been made to the manuscript to clarify our objectives and the method used. Modifications made to the discussion and the conclusion helps to better highlight the contributions of our study which brings a novelty, i.e. a better understanding of the uncertainty and measurement errors of many SWE measurement methods that are used as true SWE reference. Clarification in the scope of our conclusions with respect to manual measurement in the boreal biome has also been added. The snow pit methods presented in our study are specific to the snow conditions encountered in the boreal biome, but we believe that the analysis presented is of interest for other regions of the cryosphere.