### Answer to Charles Fierz ESSD-2021-160

We thank Charles Fierz for his very detailed review. We provide here our responses to his comments and describe how we addressed them in the revised manuscript. His original comments are in normal black font while our answers appear in blue font.

#### **General comments**

This paper presents an update of the 2019 Canadian Historical Snow Survey dataset (CHSSD). Errors in metadata as well as a large amount of duplicate data led to this overhaul. Furthermore, the dataset was renamed 'Canadian historical SWE dataset (CanSWE)' to reflect the inclusion of automated data and the weight put on water equivalent of snow cover (SWE) data. The paper is well written and well structured, describing clearly the processing steps as well as the cleaning procedures used. Great work!

The paper is timely as it emphasizes the need for standardized formats and procedures, "Python routines specific to each agency and corresponding data format were written to process the data and metadata and arrange them in a consistent NetCDF format". While I very much welcome this effort towards standardization I may have wished an even larger convergence towards WMO standards, for example regarding terminology (see comments below). However, as the authors conclude that "Regular updates are required to make such datasets useful for the community.", I would strongly suggest following WMO standards even more closely in future. For example, I anticipate a standardized WMO NetCDF format will emerge soon to which the CanSWE format may comply too.

In summary I very much appreciate the effort put in homogenising the Canadian snow survey data sets and therefore recommend accepting the paper after the authors addressed the issues below and do some minor revisions as suggested in the annotated manuscript.

The paper has been revised according to the suggestions made below by C. Fierz. In particular, we improved the terminology and the list of references to better follow the WMO standards. This also led to a new version of the CanSWE netcdf file and its related documentation in English and French on the Zenodo data portal (see <u>Canadian historical Snow Water Equivalent dataset (CanSWE, 1928-2020)</u>] <u>Zenodo</u> - Version-v2).

#### **Specific comments**

• General introduction about snow courses and snow surveys, lines 23-60:

I miss a clear statement whether you only consider snow courses as relevant measurements of water equivalent of snow cover. While on lines 39-40 you state that, "SWE observation networks using different measurements methods have been deployed at a national scale in various countries to provide valuable in situ information.", the following lines only include countries performing snow surveys, which are most typical in North America indeed, but not everywhere. I would suggest including a short paragraph on other methods, referring as you do to the 'European Snow Booklet' but also to WMO-No.8 (WMO, 2018) and also to LópezâMoreno et al. (2020).

We agree with C. Fierz that the introduction of the initial manuscript was not clear about the manual techniques used to measure SWE at single point locations. We do not consider that snow courses are the

only relevant manual measurements of SWE. Therefore, the introduction has been slightly adapted to make it clear:

Manual SWE measurements typically consist of <u>single point measurement (snow pit or single</u> <u>measurement carried out with a snow tube) or</u> multi-point gravimetric snow surveys (also known as snow transects or snow courses) collected along a pre-determined transect (WMO, 20<u>1</u>08, Lopez Moreno et al., <u>2020</u>).

National SWE measurements relying on manual <u>methods</u>snow survey are also available in several European countries: such as Finland, Estonia, Ukraine and Turkey <u>use for example snow courses whereas</u> countries such as Germany or Czech Republic rely on single point measurement-(Haberkorn, 2019).

We also added the reference to Lopez Moreno et al (2020) when mentioning the uncertainty in SWE measurement associated with the different type of snow samplers (see one comment of Reviewer 1):

Most of the agencies use the Federal snow sampler whereas the Prairie and the ESC-30 samplers are used in regions of shallow snowpack such as the Prairies or the Arctic (Table 2) ... More details about the impact of sampler type on uncertainties in SWE measurements are given in Godison et al. (1987) and Lopez Moreno et al. (2020).

• Section 3, Quality control of the final dataset :

The homogenization of data quality flags shows how important standardized report practices are.

Do I understand correctly that a H or W flag automatically results in a D flag? In other words, a quality flag set at one step influences the final number of flagged values?

In an effort to reduce the number of variables in the dataset, there are only QC flags for snw and snd. SWE and SD ranges are applied first and then the final bulk snow density calculated. SWE and SD values failing their respective tests are set to *nan* and no density value is calculated. This means that if a SWE or SD value fails its range test, no density value is calculated (set to *nan*).

Condition	snw	snd	den	Qc_flag_snw	Qc_flag_snd
SWE > range	nan	Numeric value	nan	W	
SD > range	Numeric value	nan	nan		Н
SWE and SD outside range	nan	nan	nan	W	Н
Density outside range	nan	nan	nan	D	D

 Table R2. Application of range threshold flags in order they are applied during QC for various conditions.

We made the following clarifications to the text:

When a record failed the SWE (SD) threshold but not the SD (SWE) threshold only the SWE (SD) value was set to NaN; the corresponding density value was also set to NaN and a W or H flag assigned to these records (Table 5). When a record failed the bulk snow density threshold SWE, SD and bulk snow density were set to NaN; a D flag was assigned to these records (Table 5).

• Section 4, Data availability and Table 6, lines 328-336:

From my perspective, except snw, snd, den, most of the entries in this table are observational metadata in the sense defined by WMO (WMO-No. 49, Volume I and WMO-No. 1160). It may be worth considering whether the WMO standard could be implemented in a future version of CanSWE, both regarding the name of metadata and data as well as within the NetCDF file. A note on this in the text would be appreciated.

As suggested by Charles Fierz, the term "observational metadata" is used in Table 6 and horizontal separators has been added in Table 6 to help distinguishing between the types of variables. The following sentence has also been added in Section 4:

*Future versions of CanSWE will include updated names for the observational metadata to follow the WMO standards (WMO, 2019b)* 

#### **Comments on terminology**

• 'snow water equivalent' vs "water equivalent of snow cover", lines 1 (title), 10, 23, 336 (table 6), 338:

Consider switching to new terminology introduced in WIGOS Metadata Standard (WMO-No. 1160) and WMO-No. 8, keeping SWE as abbreviation.

As recommended by C. Fierz, the new terminology is used in the revised paper. In particular, we insisted on the use of the new terminology in the first sentence of the introduction of the revised manuscript:

*Reliable in situ information of snow water equivalent <u>(SWE) or more precisely water equivalent of snow</u> <u>cover according to WMO (2018)</u>(<u>SWE)</u> – t* 

We decided to keep the title of the paper unchanged to be consistent with the name of the dataset that has been already published on Zenodo. On Zenodo, the variable names have been updated in the Netcdf file to use the new terminology. The readme files in English and French have also been changed.

• 'the depth of water that would be produced if all the snow melted', line 10:

Both the WIGOS Metadata Standard & WMO-No. 8, Vol 2, p. 13 state: "Water equivalent of snow cover (SWE) is the vertical depth of water that would be obtained if the snow cover melted completely, which equates to the snow-cover mass per unit area."

The reference definition for SWE from WMO-No. 8 is now used in the abstract and at the beginning of the introduction:

Abstract: In situ measurements of snow water equivalent (SWE) – the vertical depth of water that would be obtained if all the snow cover melted completely – ...

Introduction: Reliable in situ information of snow water equivalent (SWE) – the vertical depth of water that would be obtained if the snow cover melted completely, which equates to the snow-cover mass per unit area (WMO, 2018) – ...

•	'[derived]	bulk	snow	density':
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I very much welcome you using 'bulk snow density'!

- Consider defining it on line 211 as ratio of SWE to SD – and also in the abstract, line 14 – Consider adding 'derived' only in tables (4, 5, and 6) but not in the text (line 339)

- Use it throughout the text (see lines 245, 246, 250, 278, and 344) and not on line 255 as it is referring to a range.

Bulk snow density is new defined in the abstract: *Snow depth <u>(SD)</u> and bulk snow density (defined as the ratio of SWE to SD) are also included when available.* 

It is also defined in the main text at the end of Sect. 2.2: *Finally, where both SWE and SD measurements were available, bulk snow density was calculated from the ratio of SWE to SD and included in the final database.* 

We followed the recommendation of C. Fierz regarding the use of the term "derived" and we only kept it the different tables. It is not use anymore in the text. The term "Bulk snow density" is used systematically in the revised manuscript (except when it is referring to a range as suggested by C. Fierz).

### Comments from the pdf

P1 L 23-24: Even though the citation is correct :-), I would now prefer you referring to WMO-No. 8 and the definition therein, as detailed in my 'Comments on terminology'.

The reference to WMO (2018) is used in the manuscript.

P 1 L29: Here I would refer to WMO-No. 8 too As suggested in a comment made below about the reference section, the reference to WMO (2008) has been replaced by a reference to WMO (2018).

P2 L 33: Consider adding ref by Craig Smith?

Smith, C. D., Kontu, A., Laffin, R., and Pomeroy, J. W.: An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment, The Cryosphere, 11, 101–116, https://doi.org/10.5194/tc-11-101-2017, 2017.

Reference included.

#### P2 L 35: Kodama Correction included

P 2: 37-38 I would say that GNSS includes GPS. Thus, is there a need to cite twice the same authors? On the other side, the paper below by L. Steiner gives a view on low-cost GNSS sensors.

Steiner, L., Meindl, M., Fierz, C., Marty, C., and Geiger, A.: Monitoring snow water equivalent using lowcost GPS antennas buried underneath a snowpack, in: 2019 13th European Conference on Antennas and Propagation (EuCAP), 2019 13th European Conference on Antennas and Propagation (EuCAP), 31 March-5 April 2019, Krakow, Poland, 1–5, 2019. Thanks for this comment. We agree that GNSS includes GPS. Therefore, the sentence has been rephrased. We kept only the reference to Henkel et al. (2018) using GNSS sensors and added the reference suggested by C. Fierz:

Finally, SWE can be automatically derived by analysis of the signal from Global Navigation Satellite System receivers (Henkel et al., 2018, Steiner et al., 2019). or Global Positioning System receivers (Koch et al., 2019).

P 2 L49: Reference missing! I guess you meant:

Brun, E., Vionnet, V., Boone, A., Decharme, B., Peings, Y., Valette, R., Karbou, F., and Morin, S.: Simulation of Northern Eurasian Local Snow Depth, Mass, and Density Using a Detailed Snowpack Model and Meteorological Reanalyses, J. Hydrometeor., 14, 203–219, https://doi.org/10.1175/JHM-D-12-012.1, 2013.

#### Thanks a lot! Reference added.

#### P 3 L73: Is there public access to it?

The data were distributed on CD-ROMs (see <u>https://openpolar.no/Record/ftdatacite:oai:oai.datacite.org:9832197</u>) and the integrality of the dataset has then been transferred into the dataset published by Brown et al. (2019).

# P4 L 111: How many duplicate dates are needed to call a station a duplicate? Does this suffice to identify a station as such?

A minimum number of 10 dates was considered. As explained at L120-122 of the original manuscript, additional information on station locations and names was also considered to decide if two stations should be matched. This selection was made manually. We added to the text the information about the minimal number of dates.

P5 L 121 : See comment above, line 111. See our previous answer.

P5 L 123: I assume a matching station was not further considered as either a reference station or a neighbor to another station, correct?

Exactly. This is an iterative process so that if a merge key has already been assigned to a given station, this station is not considered in the neighborhood analysis.

P5 L 124: I think I undestand what 'reference' and 'matching' stations mean. However, the reader needs to be attentive and definitions might be helpful.

The term 'reference station' has been replaced by the term 'inspected station' and this term is now defined clearly in the text:

For each station in the CHSSD <u>(referred here as 'inspected station')</u>, all stations within a 5-km radius were identified. Each group of neighbouring stations was then manually inspected for similarities in (i) snow measurements for matching dates <u>(at least 10)</u>, (ii) station location and (iii) station name. In most cases, all three of the criteria were satisfied to trigger a decision on whether a duplicate was identified. When a duplicate was identified, the <u>inspected station and its</u> matching <u>neighbors</u> were assigned a unique merging key to be used in subsequent consolidation. If no similar stations to <u>thea</u> <u>inspected</u> reference

station were identified in a group of neighbouring stations, the <u>inspected</u> reference station was assigned its own merging key to aid in future updates to the CHSSD.

P6: Figure 2: Why not call it 'cleaned 2019 CHSSD'? This would better match the denomination in Figure 1.

Thank you for the suggestion. Figure has been updated.



P6 L 158: If possible, it would be interesting to know what the problem is such that standardization efforts elsewhere can avoid those.

The extensive historical snow dataset provided by the province of Manitoba consisted of scanned field books in pdf format over the period (1952-2017) and of a mix a scanned field books and Excel spreadsheets from 2018. The inclusion of this dataset into CanSWE would have required a significant effort that was beyond the time that was allocated to the 2021 update of CanSWE. In addition, such work needs to be done in close collaboration with the agency providing the data to benefit from its guidance. We hope this extremely valuable dataset will be processed in the future by the province of Manitoba to allow its ingestion into CanSWE.

#### P7 L 178: ranging instruments Correction included

P8 Table 2: To my knowledge this table is currently only implemented in BUFR since about 2018! You need to adapt the reference to the Manual on Codes, as indicated in the references.

As recommended, the citation WMO (2019) has been adapted in the revised manuscript to correspond to WMO Manual on Codes.

P 10 Table 3: There are 12 flags in the table. On line 228 above you state the final dataset contains 25 flags. Please comment and/or rectify.

Correction made. There are 10 agency flags for SWE and 8 for SD, not 14 and 11 as stated on line 228, now that the L and Q flags have been removed (see below).

P10 Table 3: Quite fuzzy definition. Can you expand please, for example "early morning or late afternoon"

Definition clarified. The term 'Manual snow survey conducted outside the nominal sampling period.' is now used. Early or late sampling indicates that a manual survey was made outside of the nominal sampling period; on the order of days or weeks.

P10 Table 3: Not sure I understand this correctly? Would have been meaningful to make it the 'M' flag.

The L and Q flags were relics of the older CHSSD and have been removed from the table and from the netcdf file (see the new file on Zenodo).

P10 Table 4: Add the reference to Leys et al. (2018) as a note here. Reference added as a footnote.

P10 Table 4: See comment on line 245. See our answer below.

P11 L 244: Please stick to kg m-2 Correction included.

P 11 L 245: I find it a little bit bold to call these ranges 'common'. That may be true for Canada, but not in general. Is the range 50 - 700 kg m-3 stringent at all? Both thresholds look quite 'extreme' to me. Could you please expand on this? For example, how many bulk densities in the dataset pertain to the range 50 to 200 kg m-3 and how many to the range 500 to 700 kg m-3? Is the lower range linked to low SD-values? Etc.

We agree with Charles Fierz that the terms "common" and "stringeant" used in the initial manuscript were not totally appropriate. The figure below shows the distribution of bulk snow density obtained at different sites before applying the range thresholding on density. The median bull snow density is 254 kg m<sup>-3</sup> for manual snow survey, 249 kg m<sup>-3</sup> at the location of the GMON sensors and 325 kg m<sup>-3</sup> at the location of the snow pillows. Among the manual snow survey, 2.2 % of the bulk snow density are in the range 500–700 kg m<sup>-3</sup> and 26.3 % in the range 50–200 kg m<sup>-3</sup>.



Figure: Distribution of bulk snow density before quality control.

The aims of the range thresholding for bulk density used in this paper is to identify SWE-SD pairs that are likely erroneous and to remove the corresponding values from the final dataset. Given the large variety of snow climates covered by CanSWE, we used an extended range of potential values for bulk snow density (25-700 kg m<sup>-3</sup>). A user of the dataset may want to use a more advanced QC with a density range that depends on the location and the time of year.

The revised manuscript has been adjusted as follows:

Range thresholds were used to identify spurious records in both automated and manual measurements. We adopted the thresholds outlined in Brown et al. (2019) for SWE and SD ( $0 - 3000 \text{ kg m}^{-2} \text{mm}$ ,  $0 - 8000 \text{ kg}}{\text{m}^{-2} \text{-mm}}$  for mountain) but a slightly more <u>restrictivestringent</u> range of 25 - 700 kg m<sup>-3</sup> (as opposed to  $50 - 1000 \text{ kg m}^{-3}$ ) for <u>bulk</u> snow density. These ranges are based on common ranges for SWE <u>and</u>, SD <del>and density</del> from the literature (see Braaten, 1998). <u>The range thresholding applied to bulk snow density aims at</u> identifying SWE-SD pairs that are likely erroneous.

# P 11 L 246-247: What does this mean in terms of elevation? I miss in general an altitudinal distribution of the stations.

A figure detailing the altitudinal distribution of the stations has been added to the revised version of the paper (see below). The definition of mountains used for CanSWE is extremely simple and has been selected to be consistent with the earlier versions of the CHSSD. For CanSWE, it means that specific range thresholds for SWE and SD are used for all the stations located in British Columbia and Yukon, for the stations located in the part of the Canadian Rockies in Alberta and for some stations located in the Northwestern Territories. A more relevant distinction between mountainous and non-mountainous regions (e.g., Karagulle et al., 2017) could be used for QC in future versions of CanSWE. A sentence has been added in Sect. 2.3 to mention this possibility:

## *This definition is very simple and more advanced definitions (e.g., Karagulle et al., 2017) may be considered in future version of CanSWE.*

Reference

Karagulle, D., Frye, C., Sayre, R., Breyer, S., Aniello, P., Vaughan, R., & Wright, D. (2017). Modeling global Hammond landform regions from 250-m elevation data. *Transactions in GIS*, *21*(5), 1040-1060.

P 11 L 248: Table 4? Modification included

P11 L 250: bulk density Modifications included

P 11 Figure 3: I already highly appreciate you using kg m-2. Could '-2' be written as superscript though?

Figure 3 has been updated.



P 12 Table 5: Misalignement ?

P 12 L 273: Is it really the opposite of MD? The RMD is not the opposite of the MD. We think that the term "Conversely" used in the initial manuscript was creating confusion. For this reason, it has been removed from the text in the revised version.

P 12 L 279: I would suggest to combine this sentence with the first of this paragraph. Correction included

P 12 L 283: of the Correction included

P 13 Figure 4: Caption to be improved. Are there no stations N of 75° N? Alert, Eureka? I miss the distribution by elevation.

Thanks for your comment. The map has been updated to show the stations located north of 75° N (see below). The caption is the same since the same stations are shown on the map.



Following a specific comment of Reviewer 1, the distribution of the elevation of the stations per province/territory has been added and compared to the hypsometry of the province/territory (see figure below and Fig. 6 in the revised manuscript).



#### P 18 L 344: Stick to 'derived bulk density'

Is bulk density not automatically removed if SWE or/and SD outliers are removed? => well explained in the text.

This term "bulk snow density" is now systematically used in the revised manuscript as described above in our answer to one comment regarding terminology. The bulk density is systematically removed if the SWE and/or SD outliers are removed (see our answer to the 2<sup>nd</sup> specific comment above).

P 18 L 350: What about others like Parks Canada and Avalanche Canada? The measurement networks of Parks Canada and Avalanche Canada do not contain automatic stations measuring SWE or multi-point snow surveys reporting SWE and SD. That's why their data are not considered for inclusion in CanSWE.

P 19 L 381: I had to go through https://data-donnees.ec.gc.ca/data/climate/systems/canadian-historicalsnow-survey-data/Braaten\_1998\_Canadian\_SWE\_Database.pdf to get the paper The url provided in the initial manuscript is still working so that we decided to keep it in the revised version.

P 19 L 393: Or (better?):

Choquette, Y., Ducharme, P., and Rogoza, J.: CS725, An Accurate Sensor for the Snow Water Equivalent and Soil Moisture Measurements, in: Proceedings ISSW 2013, 2013 International Snow Science Workshop, Grenoble – Chamonix Mont-Blanc, France, 931–936, 2013.

The new reference to Choquette et al. (2013) is used in the text and the citations have been updated accordingly.

P 19 L 399: Please replace with WMO-No. 8

WMO: Guide to instruments and methods of observation: Volume II - Measurement of Cryospheric Variables, 2018th ed., edited by: WMO, World Meteorological Organization, Geneva, Switzerland, 52 pp., 2018. <u>https://library.wmo.int/doc\_num.php?explnum\_id=9870</u>

The reference to Fierz et al. (2009) has been removed from the manuscript and replaced by the reference to WMO (2018).

P 21 L 442; Please add the url: <u>http://meteortest.wcc.nrcs.usda.gov:82//factpub/aib536.html</u> This url is nor working and has not been added to the revised manuscript.

P 21 L 444: Update to accepted paper Reference updated.

P21 L 447: Please add the url:

https://indico.nucleares.unam.mx/event/4/session/39/contribution/1000/material/paper/0.pdf

Url added

P 22 L 471: The reference should be replaced by:

WMO (Ed.): Guide to instruments and methods of observation: Volume II - Measurement of Cryospheric Variables, 2018th ed., World Meteorological Organization, Geneva, WMO-No. 8, 52 pp., 2018.

The new reference is used in revised manuscript and the citations have been updated accordingly.

P 22 L 473; The reference should be replaced by: The table is here:

WMO (Ed.): Manual on Codes: International codes - Part B – Binary Codes; Part C – Common Features to Binary and Alphanumeric Codes, 2019th ed., World Meteorological Organization WMO, Geneva, Switzerland, 1180 pp., 2019.

The new reference is used in revised manuscript.