Responses to referee comments

We thank the two referees for their constructive suggestions. In the following referee comments are typed in bold fonts, our responses in a regular font, and changes made in the texts in an italic font. The page and line numbers in our responses refer to those in the marked copy of the revised texts.

Referee 2

There is a lot of information in this paper that is still fairly raw. Details and context are critical but overall if the level of presented could be at a more synthesis level that would clarify the arguments. For example, a main point of this paper was identifying the different energy sources over the melt season. This was done in a qualitative manner with respect to time series of hourly energy fluxes. It would be much more compelling (and the data seems available to do this) if the authors could calculate the energy balances of the melt periods to quantitatively say how much energy for melt came from turbulent versus radiation exchange. Discuss in terms of the total energy (J) for periods of interest rather than instantaneous maximum rates (W m-2)

We agree that discussing melt in terms of energy (in Joules) as opposed to energy fluxes (in Watts) is beneficial for the manuscript. Therefore, we have added corresponding data to the manuscript as Table 4 (p.20). We also kept the energy flux data in the manuscript, as they can be directly linked to the melt rates.

There is a lot of information already on prairie snowmelt processes that seems to not be fully referenced. It would strengthen this paper to put it into a firmer context of what has already been published. Significant snowmelt research on the prairies goes back to the 1970's at the Division for Hydrology at the U of S– some of these papers are cited but many that are relevant are not.

Page 2 Line 16-18: Many authors have looked at snowmelt energy dynamics/physics on the prairies – here is a small sample. While not specific to mid-winter melts these do provide a lot of physical understanding to describe snowmelt processes in the prairies.

We have extended segment discussing prairie hydrological processes in the introduction (p.2, l.10-14) and discussion (p.11, l.8-13) citing some of the papers suggested by the reviewer. However, the space constraints prevents us from presenting more extensive review of prairie snowmelt processes.

Turbulent fluxes measured with eddy covariance and radiation from net radiometers are used to quantify the energy balance terms. There is no discussion of what these observations represent as a snow cover depletes. The EC footprint will vary with wind speed and direction and will have variable contributions from both snow -covered and snow-free ground. Are these bulk averages therefore truly indicative of the energy contributions to snowmelt? As non-snow features increase contribution to the radiometer footprint a similar influence also occurs (but no subject to wind direction or speed like the turbulent fluxes). These interpretation challenges for the energy balance observations need to be at least addressed.

Page 6 Lines 11-21: How valid for snowmelt are your eddy covariance observations when SCA is < 1?

We agree that the uncertainty in the eddy-covariance measurements needs to be explicitly mentioned. To address this issue we have added paragraph below (p.11, l.8-20):

The effect of patchy snowpack on energy fluxes is an important source of uncertainty in the measured data. The increase in measured net radiation over the melt period is caused by the reduced albedo of snow-free areas and does not represent changes in net radiation inputs into remaining snow patches. Instead a portion of extra radiative inputs is transferred towards snow patches via small-scale advection (Shook and Gray, 1997). As the top the boundary layer above snow patches is usually below the eddy-covariance sensor height (Granger et al., 2006) the energy fluxes associated with small-scale advection are excluded from measured sensible and latent heat fluxes (Harder et al., 2017). However, as such heat transfer to snow patches is ultimately driven by net radiation inputs into snow-free areas, the lack of direct measurements of small-scale advection does not fundamentally change the interpretation of the available data. Another source of uncertainty is the footprint of the eddy-covariance measurements, which routinely extends upwind by the distance of more than 100 times the sensor height and changes with time (Horst and Weil, 1994). As a result, measured fluxes reflect surface conditions (including snow cover fraction) for different areas at different times. However, the consistency between the datasets from the four weather stations indicates that temporal variation in eddy-covariance measurement footprint for each individual weather station did not have a major effect on conclusions about relative contribution of sensible heat fluxes to the midwinter and spring melts (Table 4).

The title of paper specifies that is "Effects of midwinter snowmelt on runoff generation and groundwater recharge in the Canadian prairies". Much of the paper considers the quantification of the energy sources driving mid-winter melts while runoff generation and groundwater recharge questions seem to be more ancillary. I feel that the title and paper content are somewhat disconnected.

Page 2 Line 19-21: Objectives do not reference runoff generation or groundwater recharge explicitly even though title does.

We have changed the title to "Midwinter melts in the Canadian prairies: energy balance and hydrological effects" to better align it with both objectives and the rest of the text

Both large-scale and small-scale advection is mentioned in this paper. This is only introduced in the discussion section and the differences are not clearly defined. This should be incorporated into the introduction more formally. There has been a lot of recent work that has tried to disentangle this phenomena that could benefit this discussion.

We agree that these concepts need to be mentioned earlier and amended the introduction accordingly (p.2, l.10-14):

In case of patchy snowpacks in addition to direct energy inputs, net radiation drives small-scale (intra-field) advection by warming snow-free areas above 0°C and, thus, prompting energy transfer towards remaining snow patches (Shook and Gray, 1997). Such energy transfer occurs as both sensible and latent heat fluxes (Harder et al., 2017).

Blowing snow is a critical component of the winter time mass balance. This phenomenon needs to be addressed. Can it be discounted from time-lapse camera observations? If not the sublimation of blowing snow will challenge the comparison of runoff to antecedent precipitation.

Page 6 Line 9: Is this not indicative that there is blowing snow processes occurring (specifically sublimation) and this process should be addressed?

The agreement between measured SWE and antecedent precipitation (Fig. 5) at the Triple G site (where runoff ratios were calculated) provides justification for the use of the latter parameter. While blowing snow was observed in the photos on several occasions (but not during any of the melt events), the frequent complete snowpack depletions (Fig. 4) essentially “erase” effect of all preceding blowing snow events. We have added explanation of this in the texts (p.6, l.19-22).

Paper needs more focus – less details. The science story is there: the turbulent flux energy source for mid-winter melts lead to more effective infiltration and the high radiation driven melt rates of the spring main event will have less effective infiltration and more runoff/depression focused recharge. The information presented should be limited to that which that support this main conclusion (if I interpreted correctly). In addition, the end of the discussion ends abruptly. If would be appropriate to add an additional section that discusses the implications of the mid-winter melt phenomena under climate change if there are any limitations to this type of speculation.

We acknowledge that some elements of the paper (particularly related to ponding and groundwater response) are tangential to the main conclusion about energy balance and its impact on runoff ratio. However, we believe that it is important to point out the implication of midwinter melt in runoff generation and groundwater recharge in this paper. Therefore, we kept the sections describing these processes. We have added a new paragraph at the end of the discussion (p.12, l.25-p.13, l.2) comparing the hydrological sensitivity to melt timing (this study) and precipitation characteristics (previous studies elsewhere) and climate change implications. .

The observed effect of melt timing on the hydrological processes can be compared to the sensitivity of the latter to precipitation characteristics. Several hydrological processes are more sensitive to the precipitation intensity and frequency than to its amount (Owor et al., 2009; Trenberth et al., 2003). Similarly, hydrological implications of midwinter melts can be linked to changes in the in intensity and frequency of meltwater release during snowmelt.

The importance of midwinter melts is likely to be amplified by the ongoing climate change. The current climate trends in the Canadian prairies suggest increasing likelihood of midwinter melts as decrease in number of consecutive frost days outstrips decrease in total number of frost days (Vincent et al., 2018), making periods favourable to snowpack preservation increasingly intermittent. This trend is likely to continue due to projected increase in winter temperatures throughout Canadian prairies (Shepherd and McGinn, 2003). The change is likely to be the most pronounced in the areas outside “Chinook belt” rarely affected by midwinter melts under the present climate.

Abstract: ends abruptly with three separate conclusions. Is there a way to synthesize the conclusions better?

We agree. The abstract was amended to improve coherence.

Page 1 Line 21-22: "hydrologic partitioning between streamflow and evaporative losses". What about infiltration or other sub-surface storage terms?

Streamflow and evapotranspiration represent primary ways of removing water from a given watershed (in the absence of groundwater interflow comparable to water inputs in scale) as opposed to internal redistribution within watershed (such as infiltration). We have clarified this in the revised manuscript (p.1, l.23-24).

Page 1 Line 23: this is a prairie focused paper – is there a more appropriate citation for this?

The intent behind it is to start with an overview of more geographically-generic (i.e.mountain) subset of snow hydrology before introducing prairie-specific factors in the subsequent paragraphs. We have kept this sentence unchanged.

Page 1 Line 29-30: unclear sentence

We have amended the sentence to make it more clear (p.1, l.31).

Page 2 Lines 1: snowmelt as main component of surface runoff is referenced in many other sources.

We have added "e.g." to indicate that it is one of many possible sources (p.2, l.5).

Page 3 Line 29-30: Any relationship between snow depth and density? See: Shook, K., and D.M. Gray. 1994. "Determining the Snow Water Equivalent of Shallow Prairie Snowcovers." In Eastern Snow Conference.

We re-examined the data. No obvious relationship between snow depth and density was identified neither for individual dates, nor in the dataset as the whole. We have clarified this in the texts (p.4, l.9-10) and added the dataset in question to the supplementary material.

Page 4 Line 7: What are snow gauges?

Snow gauges (Forestry Suppliers) are large plastic rulers that can be installed vertically on a ground with font large enough to be read with time-lapse cameras. This is now clarified in the texts (p.4, l.18).

Page 4 Line 15-17: How accurate how accurate is the delineation of the pond watersheds- assuming that this was used to multiply the precipitation to get total water volume.

The delineation was done using based on high resolution differential GPS survey performed specifically for this purpose. Given the topography at the Triple G site, the used value is expected to be within few percent of the true value.

Page 4 Line 28-30: Without a reference it is speculation to say that it is impossible for snowcover formation to be delayed to January.

We agree that no sufficient evidence was given to support this statement. The following sentence was added to the results section to address it (p.9, l.15-17).

Additionally, all study sites had multiple days with snow cover in December throughout the 1999-2016 period supporting the use of snow-free period in January as an indicator of midwinter melts.

Page 7 Lines 2-5: Can one assume that high latent heat fluxes are related to snow surface exchange or could this also be from a separate source like ponded meltwater in non-snow areas?

There is no sufficient evidence to pinpoint the source. Given that the large fluxes continued after depletion of the most of the snow, one can assume at least some contribution from other sources (ponded water or wet soil surfaces).

Page 8 Lines 9-12: This sentence is confusing- please clarify.

We acknowledge the readability problem. The sentence was split into two (p.9, l.27-30).

Page 10 Lines 13-15: "studies" is plural but only cite one reference?

We acknowledge the typo. The word was changed to singular (p.11, l.1).

Page 10 Line 17-20: small scale advection may be limited by the duration of a positive net radiation but the advection flux can still be large, and depending on state of snowpack and its SCA, and may lead to significant melt and SCA change. The authors should predicate this point with acknowledgment of this nuance.

The reviewer's point is well taken. The effect of small-scale advection may be amplified for low SCAs (i.e. when large snow-free area contributes to the melt of few remaining snow patches). We have revised the sentence to acknowledge the point (p.11, l.6-7).

Page 10 Line 28-31: difficult sentence

We acknowledge the readability issue. The segment was re-written (p.11, l.28-31; p.12, l.1-5):

Midwinter melts affect runoff generation, which in turn affects other components of the hydrologic cycle. The increase in runoff ratios over the course of the winter season (Fig. 10) means that the occurrence of midwinter melts tends to reduce the total amount of snowmelt runoff by shifting melt to a period with lower runoff ratios.

The likely cause for the variation in runoff ratios is the difference in energy inputs (and, hence, melt rates) between spring melt driven by net radiation and midwinter melts driven almost solely by the sensible heat flux associated with large-scale advection. Higher melt rates in spring are more likely to surpass frozen soil infiltrability, which varies in a range of 10^{-3} - 10^{2} mm h^{-1} in the prairie soils in croplands (van der Kamp et al., 2003).

Page 11 Line 3-6: To put this into context of previous research perhaps stick with nomenclature of Granger et al. 1984 who termed this "limited" infiltration.

We have changed the wording to adhere to original nomenclature by Granger et al. (p.12, l.9).

Page 11 Line 13: Wasn't this observed. Then why is this speculative with "may"?

We have changed the wording by excluding "may" (p.12, l.28).

Page 11-12 Conclusions: Portions seem to be rather repetitive from the end of the discussion?

We agree that the second paragraph of conclusions largely repeated the statements from very last paragraphs of discussion. To avoid it, the paragraph was partially deleted with some elements merged with the first paragraph.

Figure 3, 6 ,7: I find it difficult to get meaningful information with these hourly time series plotted for the four stations identified by colour. Hard to differentiate. Would it be possible to plot the total energy balance terms for the specific melt events? Overall figures have a lot of information and superimposed text which make them quite information dense.

We acknowledge that difficulties in getting the data directly from the graphs. However, we feel a need to demonstrate the inter-site similarities. We have added Table 4 (p.19) to report total energy for net radiation and sensible heat, and included all the data as supplementary material.

Please note that the absence of total energy balance (Sensible heat+Latent heat+Net Radiation) plots is due to relatively frequent gaps in latent heat flux data caused by snow and dew formation on the hygrometer sensor heads.

Figure 11: this figure highlights that there are significant differences in mid-winter melts across the Canadian Prairies -likely due to the area of influence of chinooks. Perhaps this could be elaborated in the discussion to place these findings in the context of the broader Canadian Prairies and how the influence of mid-winter melts on runoff generation will vary across the region.

We acknowledge the spatial limitation of the data coverage. While there are limits to the discussion caused by the lack of on-site data, some inference can be made (p.13, l.1-2).