Interactive comment on "Continuous in situ measurements of anchor ice formation, growth and release" by Tadros R. Ghobrial and Mark R. Loewen

Authors Response to **Referee #1** (received and published: 16 Aug 2020)

The authors wish to thank Referee #1 for the constructive comments and corrections to the discussion paper. We have responded to each of the comments from the reviewer. The comments from the reviewer are in black font and our responses are in red font.

1. **Referee #1:**
   This is a very interesting paper addressing a topic were little data is currently available. The paper both present a novel method of sampling data and presents new insights into anchor ice growth. The paper also provides a good overview of the current knowledge of anchor ice formation and growth through the introduction. I therefore think this manuscript should be accepted for publication with some minor clarifications.
   Authors Response:
   Thank you for your positive feedback on our paper and for highlighting the significance of the presented results.

2. **Referee #1:**
   The substrate studied was mounted quite close to the camera and camera frame. Could the camera frame have any impact on the flow field and thereby anchor ice deposits on the substrate plate.
   Authors Response:
   We do not think that the camera frame had a significant effect on the flow for the following reasons:
   - The camera and the frame were purposely positioned perpendicular to the flow, so that the substrate would not be inside its wake.
   - The frame was built out of 2" PVC pipe forming a hollow rectangular prism, which allowed the water to flow freely through the frame.
   - Finally, there was a 20 cm gap between the front edge of the camera and the edge of the substrate, which also helped to minimize the effect of the wake and local turbulence that would have been formed around the front vertical frame post.

3. **Referee #1:**
   How would you consider the uncertainty in manually detecting the number of crystal and crystal size given the turbid/dark nature of the example picture?
   Authors Response:
   The two sources of uncertainty in our results come from the accuracy of the scaling factor within each image, and the precision in detecting the same crystal in consecutive images. For the latter, we explored the feasibility of using thresholding image processing algorithms to detect and track individual particles, but this technique needed to be

calibrated and validated with sample data. Given the relatively reasonable number of sample images, we opted to manually select and track individual crystals. To do this, we printed and overlapped each pair of consecutive images (after applying a percentage of transparency to the image in MATLAB) to confirm the same crystal was identified throughout the series of images. We do have high confidence in this procedure when identifying individual crystals (Stage 1). For Stage 2, frazil deposition, the presence of a relatively high concentration of frazil crystals in the flow as well as higher turbidity levels, increased the uncertainty in detecting the top edge of the in-focus frazil deposition. See also our response number 3 to RC3 for a more quantitative description of the level of uncertainty in our scaling factor. We will add a section discussing the sources of uncertainty to the discussion section.

4. **Referee #1:**
   Did you compare the anchor ice forming on the substrate plate with anchor ice deposits on the natural substrate nearby the study site?
   Authors Response:
   During each deployment we frequently visited the site to maintain the platform as well as to take pictures of sampled anchor ice depositing on the natural bed. Although we did observe anchor ice forming nearby on the bed during each event, we did not compare the characteristics of the anchor ice deposits forming on the river bed and the constructed substrate. A thorough comparison would likely have required the collection of anchor ice samples and some additional measurements which was outside of the scope of this study.

5. **Referee #1:**
   You see anchor ice releases when the water is still supercooled and even when temperature decreases. This is an interesting observation and different from what we have observed in our anchor ice studies. What mechanism caused this? Forces from the water flow? On page 14 from line 30 you discuss the effect of rising stage e.g. from hydropeaking so this might be an explanation why ice released when the supercooling was still quite high.
   Authors Response:
   Thank you for highlighting this phenomenon. We did see a trend in the four release events (Events C to F) of release occurring when water levels were rising or were approaching the daily maximum (Page 15, line 3). This may indicate that hydrodynamic forces played a role in the release of these anchor ice accumulations. This is something we plan to investigate in more detail in the future.

6. **Referee #1:**
   You define four stages of formation of growth. E.g. stage 2 did not appear in all experiments. Is this because this stage is not detectable or because the formation did not pass through this stage? Can you say something more on that, and do you think these four stages appear at all anchor ice formation events?
   Authors Response:

This is a very important point. Stage 2 was defined as the transition between the rapid crystal growth stage (Stage 1), and the slower "linear" growth by frazil deposition stage (Stage 3). So, by definition, Stage 2 would possibly be observed whenever the anchor ice event was initiated by crystal growth (Stage 1). In our data, we did observe both scenarios. Page 11, line 29-31 reads:" Three of the six anchor ice events (Events B, C, and D) were observed to be initiated by in situ crystal growth (Stage 1) followed by frazil deposition. For the remaining three events (Events A, E, and F) no in situ crystal growth was observed and it appeared that the accumulations grew only by frazil deposition (Stage 2 and 3)". More research is needed to identify under which conditions, we would expect to "see" which mode of initiation.

7. **Referee #1:**
   Did you observe any difference in water temperature between the two sensors on the submerged system? I assume the temperature used is measured with the sensor closest to the substrate.
   Authors Response:
   Our data showed that water temperature measurements from both sensors were almost identical within the stated accuracy of the sensors. Therefore, we decided to only show the data from the sensor on the substrate since it is closer to the anchor ice formation. <u>We will add this note to the manuscript when introducing these results in Page 9, line 5</u>.

8. **Referee #1:**
   Page13, line 10-25. Could the thick layers of anchor ice under the border ice be driven by a larger accumulation of drifting frazil? Was the structure of the deep depositions similar to the anchor ice detected at the study site? This accumulation of ice with a foundation on anchor ice is also often seen in steeper streams and where anchor ice dams form.
   Authors Response:
   This is an interesting comment. We agree that the thick "anchor ice" observed under the border ice may not be due entirely to growth of locally forming anchor ice. We did not collect samples of these deep deposits, so we do not know if the structure was similar to open water anchor ice formations. <u>A comment noting that "the sources of those thick deposits may be due to local anchor ice growth, or accumulation of floating frazil slush or stacking of released anchor ice from upstream, or a combination of any of these phenomenon" will be added to the revised paper</u>.

9. **Referee #1:**
   Page 14, line 5-10: Did you try to estimate the heat flux during the experiments? Do you have any indication of heat transfer from the sediments? This is an interesting observation, see also comment above.
   Authors Response:
   In this study we did not estimate each heat flux component during each event, but we qualitatively discussed the expected effects of meteorological forcing on the release of

anchor ice (Page 14, line 5-10). In addition, we estimated the maximum net heat loss from the water to be 300 W/m^2 using a liner heat transfer equation (Page 16, line 2). We did not conduct direct measurements of water temperatures in the riverbed that would be required to estimate heat transfer from the sediment, but we thought it was worthwhile to list it as a potential source of heat input that might weaken the bond between anchor ice and the substrate (Page 14, line 4).

10. Referee #1:

Page 15, from line 5: This section is not very clear to me. Are you looking at providing better parametrization for modelling? I think this could have been made clearer. As asked above, can you estimate the heat flux for your site based on climate data to test the assumptions made in the computation?

Authors Response:

We did estimate a maximum net heat flux between air and water using the linear heat transfer equation to be 300 W/m^2 (Page 16, line 2). The objective of this section of the discussion was to use the measured rates of growth to provide a realistic range of values for suspended frazil concentration and the porosity of anchor ice using Equation 1. This is discussed in page 15 and 16. We will review and if necessary, rewrite parts of this section to improve its clarity and better explain the rationale.

11. Referee #1:

Figure 5 – 8: I can see the reason for having the same scale for Water temp for all figures, but this obscure small variations in some of the graphs. Maybe this scale could vary between graphs?

Authors Response:

We think it is easier for the reader to compare between events when we use the same scale. For most of the events the small variations in the water temperatures are insignificant and within the stated sensors accuracy of ±0.002 °C.

12. Referee #1:

Figure 12: What causes the large scatter in the growth rates for event C? This is not discussed in the text where it seems like the growth followed the linear models, which in figure 12 is reasonable for B/D but not for C.?

Authors Response:

This is a very valid comment. We do not know the reason for the scatter in Event C. This scatter shows that crystals can grow at significantly different rates during the same time interval and in close proximity to each other. This might be because crystals can originate from different parts of the substrate and as a result, they will be exposed to different flow conditions. We will add a discussion in Page 12 line 19-29, to highlight this phenomenon.