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 **Dr Edward Kempema** kempema@uwyo.edu (Referee #4) (received and published: 3 September 2020)

The authors wish to thank Dr. Kempema for the constructive comments and suggested corrections to the discussion paper. We have responded to each of his comments. The comments are in black font and our responses are in red font.

1. **Dr. Kempema:**
I think a reasonable argument could be made that our understanding of anchor ice initiation and growth have not advanced significantly since Altberg (1936) published his findings 84 years ago. We have a particularly poor understanding of the relative importance of frazil accretion versus in situ ice growth in accumulating anchor ice masses (something Altberg struggled with). The paper by Ghobrial and Loewen describes their technique of using a high-resolution camera package to measure the growth of anchor ice (both individual ice crystals and anchor ice accumulations) on a natural cobble substrate in the North Saskatchewan River. Their paper presents preliminary data on frazil accumulation versus in situ anchor ice growth mechanisms based on their imaging system. This paper makes a significant contribution to the ice community's understanding of anchor ice formation in this natural setting.
Authors Response:
Thank you for your positive feedback on our paper and for highlighting the significance of the presented results.

2. **Dr. Kempema:**
In my opinion the authors give short shrift to Kempema and Ettema (2013, 2016; the 2016 paper is an expanded version of the 2013 conference proceedings). These two papers describe the use of a high-resolution camera system to determine anchor-ice crystal growth rates on a wedge wire screen element placed in the Laramie River during the 2012-2013 winter. They were able to document the growth rate of individual anchor-ice ice crystals in anchor-ice masses with this system, which was similar in concept to the camera system described by Ghobrial and Loewen. Although the camera systems in both studies were similar, the two systems differed in two important ways: (1) Kempema and Ettema focused on anchor ice growth on an intake screen while the present paper focus on anchor ice on the bed; and (2) Ghobrial's and Lowen's system is much more advanced that that used by Kempema and Ettema. Specifically, the Ghobrial and Loewen system includes precise water temperature measurements to relate ice growth to supercooling levals and their camera system included a fixed, consistent cobble bed, a better camera, and heating elements to keep ice off the camera lens. This system is a major advance over what is described in Kempema and Ettema (2013, 2016) This made it possible for the authors to measure the increase of anchor-ice mass thickness in addition to measuring individual ice crystal growth. Ghobrial and Loewen

reference Kempema and Ettema (2013) but appear to dismiss their reported ice crystal growth rates of ~1-4 cm/hr on the basis that the wedge wire screen was placed in the water column where heat transfer was greater relative to the bed. They suggest this might explain the higher ice-crystal growth rates reported by Kempema & Ettema relative to their findings (1-3 cm/hr) (P12L24-29, P: page number, L: line number). Considering the paucity of attached anchor ice crystal growth rates in natural settings reported in the literature (39 to my knowledge) it seems curious to dismiss ~3/4 of the observations on the basis that they were taken at the wrong point in the water column. While acknowledging that the goals of the two projects were somewhat different and the substrates were very different, my bias is that anchor ice is anchor ice, regardless of the substrate it forms on. Kempema and Ettema (2013, 2016) make the case that "frazil ice blockages" are, in fact, anchor ice. I agree with Ghobrial and Loewen that underwater ice crystal growth rates are determined by turbulent heat transfer (Altberg also concurred), but point out that every growing underwater ice crystal is in a unique, local turbulent/heat transfer environment and so will have a unique morphology representing its growth history. This reinforces my argument for including, not downplaying (dismissing?), the Kempema and Ettema (2013, 2016) ice crystal growth rates. Considering the different settings (river morphologies, water depths, weather conditions, and substrates), the observed range of growth rates are very consistent. A very real contribution of the Ghobrial and Loewen paper is that it describes a system (camera, processing software, temperature recorders, consistent bed strucure) that can be used to more (and more detailed) observations in the future.

Authors Response:

Thank you for highlighting the work of Altberg (1936) and Kempema and Ettema (2013 and 2016). We did refer to the system and the growth rates reported by Kempema and Ettema (2013) in page 12, lines 23-29. Nevertheless, <u>we agree that it is important to include a more detailed description of their system and findings in the literature review as well as the </u>discussion section. Also, the following references will be added to the revised paper:

- Altberg, W.J. 1936, Twenty years of work in the domain of underwater ice formation, International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Bulletin 23 373-407.
- Kempema Edward, W. and Ettema, R. 2016, Fish, Ice, and Wedge-Wire Screen Water Intakes, Journal of Cold Regions Engineering, 30-2, doi:10.1061/(ASCE)CR.1943-5495.0000097.

3. **<u>Dr. Kempema:</u>**

Ghobrial and Loewen describe observations of anchor ice masses breaking the surface of the water at 1.6 m water depth near their deployment site (p13L18-25). Using their measured ice growth rates, they calculate it would take 267 hours to grow this accumulation of anchor ice. Their Figure 4 shows a 10-day period when conditions appear to have been conducive to a multi-day anchor ice cycle that could have produced this amount of ice at the rates reported in this paper. Unfortunately, the authors do not report the date of their observation. Alternatively, anchor ice growth rates may have been higher in the deeper water or released anchor ice masses (possibly negatively buoyant) were stacked one on top of the other to this thickness. The use of an average growth rate to calculate a growth time implies a much greater confidence in the average than is warranted. A possible example of released anchor ice stacking can be seen at 2:08 to 2:11 (minutes:seconds) in the manuscript video (clock time December 4, 2018 05:16 to 05:41). A frazil floc or released anchor ice mass appears on to the left of the PVC pipe in the image frame at the start of this sequence and disappears at the end. Similar processes, with potentially much larger ice masses, could have built the observed 1.6 m thick accumulation in a relatively short time. In my opinion, it would be good to discuss these other methods of building up thick layers of anchor ice (if one can call accumulations of released ice that) rather than present the calculation. In this same section, the authors state that several auger holes showed anchor ice in contact with the underside of border ice in 1.5 m water depth. It is very common for released anchor ice to be advected under border ice in my experience. I would argue that the observation of large ice crystals has no relevance vis a vis local anchor ice growth or formation. This gets to be something of a semantic argument. Once anchor ice is released from the bed it is no longer, strictly speaking, anchor ice. By extension accumulations of this released anchor ice (slush ice?) under border ice are no longer anchor ice unless they are attached, as opposed to in contact with, the bed.

Authors Response:

We want to thank Dr Kempema for providing these descriptions of other possible sources and mechanisms of anchor ice accumulation such as the effect of stacking of released anchor ice or buildup of suspended frazil slush to existing anchor ice accumulations. As suggested, we will include a more in-depth discussion of possible explanations for the thick deposits of anchor ice that we observed and also for the thick accumulations we observed under border ice.

4. **Dr. Kempema:**

The three panels in Figure 10 purport to show (a) curved needle crystals, (b) platelet ice, and (c) ice disks. However, (a) also contains ice disks (I would call them modified frazil crystals) on the left and what looks like platelet ice on the right side of the figure; (b) does look like platelet ice; and (c) contains at least as much platelet ice as disk ice. Perhaps you could put an arrow in each panel to identify the ice crystal morphology they are meant to show? I actually think these are wonderful images, because they show the complexity that is common in an anchor ice mass (also shown in Figure 9). My experience is that most anchor ice consists of a mix of ice crystal morphologies that represent their past growth history. These photos show this wonderfully.

Authors Response:

Thank you for highlighting the importance of showing such images of anchor ice crystals. As suggested, we will add arrows to the photographs indicating the different crystal morphologies in each image. We will also add a brief discussion of how these images demonstrate the complexity that is commonly observed in anchor ice accumulations.

5. **Dr. Kempema:**

This paper made me rethink my own concepts on anchor ice formation, which made it a pleasure to read. The paper represents a significant contribution to anchor ice research and the expectation that this technique will produce more insights on anchor ice growth mechanisms in the future.

Authors Response:

Thank you for your positive comments and encouragement.

Technical Comments:

6. **Dr. Kempema:**
   P1L7: suggest changing "cooled to slightly below 0oC" to "cooled to slightly below the freezing point" to make the definition of supercooling clear (e.g. ocean water at -1 oC is not supercooled).
   Authors Response:
   Agree.

7. **Dr. Kempema:**
   P3L4: Add "and" before "for collecting".
   Authors Response:
   Agree.

8. **Dr. Kempema:**
   P3L8: change "crystals layers" to "crystal layers"
   Authors Response:
   Agree.

9. **Dr. Kempema:**
   P4L34: "the crystals showed grew preferentially perpendicular to the flow" remove "showed"?
   Authors Response:
   Agree.

10. **Dr. Kempema:**
    P6L4: "1,800 m above sea level" not sure what this refers to. Is it the highest peak in the drainage (seems unlikely), the average elevation of the upper drainage, or what?
    Authors Response:
    This refers to the mouth of the glacier feeding into the North Saskatchewan River.

11. **Dr. Kempema:**
    P7,L5-10: What size classification scheme did you use? Wentworth's size classification lists sediment used in this study in the cobble size range. Gravel is not used in Wentworth's classification and boulders are >256 mm in diameter.
    Authors Response:

We performed a sieve analysis of the bed samples and used sediment particles on the substrate that ranged in size between 3.8 cm and 12.5 cm. According to the classification of naturally occurring sediments reported in the USGS Scientific Investigations Report 2019–5073, the range of sediment size used on the substrate would be classified as very coarse pebble gravel and fine cobble gravel.

12. <u>Dr. Kempema:</u>

P15L18-19: "Newly formed anchor ice accumulations likely have higher porosities because they often do not maintain their structural integrity when sampling is attempted." Is this based on personal observation or a literature reference? If this is your observation, it seems a little odd that it shows up in the discussion. At least, please, make the source clear.

<u>Authors Response:</u>

This was based on our observations and the observations of Dubé et al. (2014). We will revise the paper accordingly.