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.

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 #2** (received and published: 23 August 2020)

The authors wish to thank Referee #2 for their constructive comments and suggestions. 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 #2:**
   This is an interesting paper presenting some novel finds on anchor ice formation. This paper should have a large impact on the readership. Some minor revisions are required before it is published.
   Authors Response:
   Thank you for your positive feedback on our paper and for highlighting the significance of the presented results.

2. **Referee #2:**
   Page 1, Line 24: rapid what?
   Authors Response:
   We will clarify the last sentence of the abstract to read:" Anchor ice was observed releasing from the bed in three modes referred to as lifting of the entire accumulation, shearing of layers of the accumulation and rapid release of the entire accumulation."

3. **Referee #2:**
   Page 4, Line 9: should read "ice accumulation densities"?
   Authors Response:
   Thank you for catching this mistake. The text will be updated as suggested.

4. **Referee #2:**
   Page 7, Line 8: was the flat side facing down or up on the plywood base?
   Authors Response:
   The flat side of the substrate materials were facing down on the plywood base to increase the gluing contact surface between the base and the gravel.

5. **Referee #2:**
   Page 7, Line 20: What did the change in camera housing do?
   Authors Response:
   The camera housing was changed due to some damage to the original housing resulting in water leaking inside the case.

6. **Referee #2:**
   Page 10, Line 30: should read "ice crystal growth"?

<u>Authors Response:</u>
Thank you for catching this mistake. The text will be updated as suggested.

7. **<u>Referee #2:</u>**
   Page 10, Line 33: should read "grew at approximately linear rates …".
   <u>Authors Response:</u>
   Thank you for catching this mistake. The text will be updated as suggested.

8. **<u>Referee #2:</u>**
   Page 12. Line 9: should read: "crystals, or".
   <u>Authors Response:</u>
   Thank you for catching this mistake. The text will be updated as suggested.

9. **<u>Referee #2:</u>**
   Page 13, Line 13; should read "The crystal sizes".
   <u>Authors Response:</u>
   Thank you for catching this mistake. The text will be updated as suggested.

10. **<u>Referee #2:</u>**
    Page 15, Line 12: should read: "to be predicted at each"?
    <u>Authors Response:</u>
    Thank you for catching this mistake. The text will be updated as suggested.

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 #3** (received and published: 25 August 2020)

The authors wish to thank Referee #3 for the constructive comments and suggested 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 #3:**
   The authors have conducted a novel field study of anchor ice formation, growth and release that clearly addresses a knowledge gap in the literature. They have provided a thorough review of the current state of knowledge of anchor ice processes and have complemented this very well with their new field measurements. The paper is well written and will be of interest to many people in the river ice engineering field.
   Authors Response:
   Thank you for your positive feedback on our paper and for highlighting the significance of the presented results.

2. **Referee #3:**
   The authors note that several previous investigators have discussed correlations between anchor ice characteristics and the flow Froude or Reynolds number. Perhaps it would be useful to report these two values for each of the events summarized in Table 2.
   Authors Response:
   This is a very useful suggestion. Unfortunately, during these measurements, we did not measure local velocities and depths. We did make measurements of these flow parameters in the following year of measurements and will include them in future publications.

3. **Referee #3:**
   There is discussion on the uncertainty of measured parameters (ie. crystal growth rate, thickness). Perhaps this could be added. I suspect that while the camera resolution (ie. pixel size) might suggest a high degree of accuracy, the problems associated with the depth of field when measuring the anchor ice thickness might be more significant.
   Authors Response:
   We agree that a discussion on the sources of uncertainty is needed. This comment was also raised by Referee #1. We identified three the sources of uncertainty: (1) the camera resolution, (2) the precision in detecting the same crystal between consecutive images, and (3) image clarity when trying to identify the in-focus anchor ice that we tracked to measure growth rates. We agree that the high camera resolution only indicates the maximum possible accuracy and that other factors will govern the actual measurement accuracy. Images clarity did affect the uncertainty in tracking individual crystals and top of ice accumulation. When tracking individual crystals, we printed and overlapped each

pair of consecutive images (after applying a percentage of transparency to the image in MATLAB) to confirm that 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, high concentrations 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. This leads to the third source of uncertainty the accuracy of the scaling factor. The in-focus section of the substrate used for scaling anchor ice sizes was 40 cm away from the face of the lens. We estimate that the vast majority of observed anchor ice was located between 30 to 50 cm away from the camera, ±10 cm from the focus distance. If we considered these two extreme cases (i.e. ± 10 cm), the resulting expected error in estimating anchor ice dimensions (crystals or depth of deposition) would be approximately ± 25%. We will include a section in the discussion addressing the sources of uncertainty.

4. **Referee #3:**

   I am unfamiliar with the local hydraulics, so I am unable to differentiate between the normal diurnal water level variations because of upstream hydropeaking versus staging during anchor ice formation and de-staging during anchor ice release. Were the impacts of anchor ice of sufficient magnitude to be observable in the water level measurements?

   Authors Response:

   Based on our knowledge of the site, we do not think that anchor ice formation and release have any significant effects on the change in water levels. The diurnal variation of water levels appears to be entirely controlled by the hydropeaking from the dam's operation upstream. This was observed during the first three deployment. During DEP-4 (Events E and F), the continuously rising water levels were attributed to the staging-up due to ice cover formation downstream. We did discuss our assessment of the water level data in Page 14 line 28 to Page 15 line 4.

5. **Referee #3:**

   Line 2 of the abstract – even though line 1 notes both turbulence and supercooling, line 2 starts over and says that supercooled water generates frazil ice and does not mention the concurrent requirement of sufficient fluid turbulence.

   Authors Response:

   Thank you for your comment. Line 2 of the abstract will be updated to read:" In supercooled turbulent water…".

6. **Referee #3:**

   Stage 4 is listed as the release phase (Pg 10, line 25) however, on Figure 11 Stage 4 is shown to have a very rapid increase in thickness, as opposed to a drop in thickness down to zero.

   Authors Response:

Thank you for clarifying this. The label for Stage 4 in Figure 11 was to highlight the start of the "lifting" release mechanism before the total removal of the anchor ice accumulation. We will update the figure caption to clarify this issue.

7. **Referee #3:**
   Page 12, line 25 – Did Kempema and Ettema report observed water temperature measurements at the wedge wire screens? If the water was more supercooled this could also explain the higher growth rate.
   Authors Response:
   Unfortunately, Kempema and Ettema did not measure water temperatures in their setup. We attributed their higher growth rates to higher flow turbulence (the wedge wire screen being installed 23 cm above the bed).

8. **Referee #3:**
   Page 14, line 1 – The substrate thermometer looked to be covered in anchor ice in the photo, which may prevent it from providing an accurate measure of the water temperature. Did you compare with the thermometer mounted higher up on the frame?
   Authors Response:
   Yes, we did compare results from both sensors and the 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.

9. **Referee #3:**
   Page 16, line 6: is the first sentence too general? You've listed a few field measurements of anchor ice growth in your lit review section.
   Authors Response:
   Yes, we agree with your comment. We will update the sentence to read:" <u>The first continuous field measurements of the anchor ice cycle including, initiation, growth and release mechanisms were captured in this study"</u>.

10. **Referee #3:**
    Page 16, line 9: the mode name 'rapid' could be more descriptive in my opinion.
    Authors Response:
    The only alternative to "rapid" that we thought might be applicable was "instantaneous". However, because our images were taken every 5 min we did not think it was accurate to call this instantaneous release.

11. **Referee #3:**
    Pg. 1, Line 14 – rewording is required: '... have been reported to study'; 'but'
    Authors Response:
    Agreed. The sentence will be reworded to read: "<u>Although detailed laboratory experiments studying anchor ice have been reported in the literature, but very few field measurements of anchor ice processes have been reported."</u>.

12. **Referee #3:**

Pg. 1, Line 26 – repetitive 'defined'

Authors Response:

Agreed. The sentence will be reworded to read: "Anchor ice is described as ice that is attached or "anchored" to the bed of natural water bodies (rivers, lakes or sea floors) as defined by World Meteorological Organization (1970).".

13. **Referee #3:**

Pg. 3, Line 23 – increase with increasing Froude number; lines 24 – 26 – changing from present to past tense a couple of times. This also occurs at other locations within the manuscript.

Authors Response:

Thank you for catching this mistake. The sentence in line 22 will read:" anchor ice growth rates and densities increased with increasing Froude number." We will also review the manuscript to verify consistency in using the correct tense.

14. **Referee #3:**

Pg. 3, line28 – 'have been reported' rather than 'has been reported'.

Authors Response:

Updated.

15. **Referee #3:**

Pg. 3, line28 – 'have been reported' rather than 'has been reported'.

Authors Response:

Updated.

16. **Referee #3:**

Pg. 4, line 2 – reword '…provided many valuable information'.

Authors Response:

Agreed. The sentence will read:" Despite these limitations, field studies have significantly advanced our knowledge of anchor ice processes".

17. **Referee #3:**

Pg. 4, line 34 – reword '… crystals showed grew preferentially…'.

Authors Response:

Agreed. The sentence will read:" In both cases, the crystals showed preferential growth perpendicular to the flow.".

18. **Referee #3:**

Pg. 14, line 33 - … release of event C anchor ice

Authors Response:

Thank you for catching this mistake. We will update the sentence to read:" The release of event C anchor ice coincided with a peak in the daily water levels of 3.38 m."

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, 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 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. **Dr. Kempema:**

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.

Continuous in situ measurements of anchor ice formation, growth and release

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Abstract. In northern rivers, turbulent water becomes supercooled (i.e. cooled to slightly below ~~0 °C~~the freezing point) when exposed to freezing air temperatures. In supercooled turbulent water, frazil (small ice disks) crystals are generated in the water column and anchor ice starts to form on the bed. Two anchor ice formation mechanisms have been reported in the literature: either by the accumulation of suspended frazil particles, which are adhesive (sticky) in nature, on the river bed; or by in situ growth of ice crystals on the bed material. Once anchor ice has formed on the bed, the accumulation typically continues to grow (either due to further frazil accumulation and/or crystal growth) until release occurs due to mechanical (shear force by the flow or buoyancy of the accumulation) or thermal (warming of the water column which weakens the ice-substrate bond) forcing or a combination of the two. ~~Although~~There have been a number of detailed laboratory ~~experiment~~studies~~s studying~~ of anchor ice ~~have been~~ reported in the literature, but very few field measurements of anchor ice processes have been reported. ~~Although detailed laboratory experiments have been reported to study anchor ice, but very few field measurements of anchor ice processes have been reported.~~ These measurements have relied on either sampling anchor ice accumulations from the river bed, or qualitatively describing the observed formation and release. In this study, a custom-built imaging system (camera and lighting) was developed to capture high-resolution digital images of anchor ice formation and release on the river bed. A total of six anchor ice events were successfully captured in the time-lapse images and for the first time, the different initiation, growth and release mechanisms were measured in the field. Four stages of the anchor ice cycle were identified, namely: Stage 1: initiation by in situ crystal growth, Stage 2: transitional phase, Stage 3: linear growth, and Stage 4: release phase. Anchor ice initiation due to in situ growth was observed in three events and in the remainder the accumulation appeared to be initiated by frazil deposition. The Stage 1 growth rates ranged from 1.3 to 2.0 cm/hr and the Stage 2 and 3 growth rates varied from 0.3 to 0.9 cm/hr. Anchor ice was observed releasing from the bed in three modes~~; referred to as~~ lifting of the entire accumulation, shearing of layers of the accumulation and rapid release of the entire accumulation.~~Anchor ice was observed releasing from the bed in three modes referred to as lifting, shearing and rapid.~~

1 Introduction

Anchor ice is described as ice that is attached or "anchored" to the bed of natural water bodies (rivers, lakes or sea floors) as defined by World Meteorological Organization (1970).Anchor ice is defined as ice that is attached or "anchored" to the bed of natural water bodies (rivers, lakes or sea floors) as defined by World Meteorological Organization (1970). Although observations on the formation of anchor ice in rivers have been documented since the 18th century (Barnes, 1908; Altberg, 1936), the mechanisms of formation, growth and release, as well as its overall effect on river ice processes, is still a relatively unstudied phenomenon (Tsang, 1982; Beltaos, 2013). Anchor ice formation and release can cause significant changes to the river bed geometry, affect water levels and discharges, and consequently loss of hydropower production during freeze-up seasons (e.g. Girling and Groeneveld, 1999; Jasek et al., 2015). Anchor ice released from the bottom often contains significant amounts of bed materials which contributes to the sediment transported in river systems (e.g. Kempema and Ettema, 2011; Kalke et al., 2017). Recently it has been shown that the duration and extent of anchor ice cycles has an effect on algae growth rates and its total biomass (Suzuki et al., 2018). Also, fish habitat, in particular fish spawning can be affected by the formation of anchor ice on the bed which can block oxygen supply to substrate water and freeze the eggs under the ice (e.g. Prowse, 2001; Brown et al., 2011). Available river ice numerical models have attempted to include the effects of anchor ice in hydraulic modelling. These models have mostly relied on empirical or semi-empirical relations (e.g. Shen, 2010; Lindenschmidt, 2017; Blackburn and She, 2019; Makkonen and Tikanmäki, 2018) but the development of physically-based models has been challenging due to the lack of accurate field measurements of anchor ice formation, growth and release.

The process of anchor ice formation starts when surface water becomes supercooled (i.e. water is cooled below its freezing point) typically due to freezing air temperatures. In the presence of sufficient flow turbulence, the supercooled surface water is transported to lower layers and quickly reaches the river bed (Daly, 1994). In supercooled turbulent water, active (sticky) frazil ice crystals are typically generated in the water column and subsequently anchor ice may also form on the river bed. It has been established that anchor ice formation can be initiated by two processes: in situ growth of ice crystals (i.e. nucleation of ice crystals atop the bed material) and/or accretion (i.e. deposition) of active frazil particles on submerged objects (Tsang, 1982). After the initial formation of anchor ice crystals on the river bed, the accumulation continues to grow either by crystal growth due to heat loss to the surrounding supercooled water, and/or by further deposition of suspended frazil particles (Osterkamp and Gosink, 1983; Qu and Doering, 2007). The final thickness of the anchor ice layer is limited by several factors including the absence of supercooled water, the stream flow depth (although in some cases the accumulation can emerge above the water surface forming anchor ice dams), the growth of an overlaying surface layer of stationary or border ice, or the release of the anchor ice accumulation from the bottom (e.g. Osterkamp and Gosink, 1983; Beltaos, 2013; Turcotte et al., 2013). Increasing anchor ice thickness coincides with increases in the drag and buoyancy forces acting on the accumulation. Anchor ice release is thought to occur due to mechanical or thermal forcing or a combination of the two (e.g. Parkinson, 1984; Shen, 2005). Mechanical release of anchor ice occurs when the buoyancy and drag forces are greater than the ice-substrate bond, or when these forces are greater than the submerged weight of the anchor ice and the attached bed materials (sands, gravel, or boulders). This latter mechanism results in rafting of river bed materials (sediments) as released anchor ice pans are advected downstream (Kempema and Ettema, 2011; Kalke et al., 2017). Anchor ice has often been observed to release in the morning following cold and clear nights (Barnes, 1908; Kempema et al., 2001; Daly and Ettema 2006) and this has been attributed to warming of the water by solar radiation that weakens the ice-substrate bond leading to thermal release.

Many of the physical measurements available on anchor ice formation, growth and release, are from detailed laboratory experiments (Altberg, 1936; Kerr et al., 2002; Doering et al., 2001; Qu and Doering, 2007). In laboratories, the ambient conditions are controlled (air temperature, discharge, and channel characteristics) and the environment is favourable for conducting detailed measurements (e.g. video recordings, depth and velocity profiles) and for collecting samples of anchor ice accumulations. Altberg (1936) conducted the first reported controlled laboratory experiments to study anchor ice using a race-track recirculating flume. ~~His observations~~He concluded ~~the~~that two fundamental conditions must exist for anchor ice formation: ~~the necessity of~~ supercooling of the water (thermodynamic effect) and flow turbulence (dynamic effect). Kerr et al. (2002) conducted a laboratory study on anchor ice formation and its hydraulic effects on a gravel bed in a refrigerated flume. In all of their experimental runs, they observed anchor ice initiation only due to frazil deposition/attachment to the bed (i.e. no in situ growth). They documented three distinct stages of anchor ice growth: initial, transitional, and final growth stages. The initial stage (referred to as “Stage 1” herein), is the formation of the first visible anchor ice crystal~~s~~ layers on the substrate. This stage was characterized by faster growth rates and uneven appearance along the bed. The transitional stage (referred to as “Stage 2” herein) started once the accumulations began to emerge out of the substrate and protruded into the flow. The hydrodynamic drag forces acting on the accumulation caused the flattening or release of the anchor ice formation. During this transitional stage, anchor ice accumulation either continued to increase due to frazil deposition, or decreased slightly due to its release into the flow. The final growth stage (referred to as “Stage 3” herein) was defined as the nearly uniform (linear) and slower growth rates of anchor ice thickness due to continuous frazil deposition. At this stage, individual anchor ice forms were not distinguishable. The measured growth rates ranged between ~ 0.02 and 0.05 cm/°C-hr, which for an average air temperature of -16.0 °C translates to a growth rate between 0.4 and 0.8 cm/hr. Although they reported that anchor ice released only at Reynolds number less than ~22,000, it is worth noting that they only tested two values of Reynolds numbers (i.e. 21,800 and 29,000).

Doering et al. (2001) and Qu and Doering (2007) conducted laboratory experiments on anchor ice evolution in a counter rotating flume. They measured growth rates between 0.3 and 0.7 cm/hr and their data suggested that anchor ice growth rates and densities increased with increasing~~the~~ Froude number. Although they visually observed that anchor ice always initiated with frazil deposition, with a careful interpretation of the water temperature (supercooling) curves, they were able to attribute some of the continuous growth of anchor ice thickness to the in situ growth of the crystals. They found that gravel size did not have an effect on the formation (initiation) mechanisms, but they found that anchor ice ~~releases~~ released more easily when it was attached to smaller gravel particles. They also observed that anchor ice ~~tends~~ tended to release when the Reynolds number is less than 42,000.

Several field observations on anchor ice processes ~~has~~ have been reported in the literature using grab sampling techniques, on-shore photographs, and intermittent underwater photography. Therefore, these observations were mostly limited to the qualitative description of anchor ice properties such as shape, thickness, extent of formation and release, and how these properties are related to hydro-meteorological conditions (e.g. Hirayama et al., 1997; Terada et al., 1998; Turcotte and Morse, 2011; Nafziger et al., 2017). Reasons for this limitation include the need for supercooled water, that anchor ice typically forms during night time when visibility is low, the difficulty of predicting where anchor ice might form, and of course the limitation of working in cold weather. As a result, continuous measurements of anchor ice growth rates and observations of initiation processes (i.e. in situ crystal growth versus frazil particles deposition) have not been made in the field. Despite these limitations, field studies have significantly advanced our knowledge of anchor ice processes~~advanced our knowledge of anchor ice processes and provided many valuable information~~.

Hirayama et al. (1997) conducted a three years study on a small gravel stream (6 to 9 m wide and 0.3 to 0.6 m deep) in Hokkaido, Japan. They mapped the Froude number contours within the study reach and showed that anchor ice only forms when the Froude number is between 0.2 and 1.5. They reported that sampled anchor ice masses consisted mainly of needle-like crystals which were growing either in the upstream or the downstream direction of the flow. They showed that the thickness and volume of anchor ice accumulations increased with the cumulative degree hour of freezing of air temperature, and reported anchor ice thicknesses ranging between 3 and 17 cm. Also, they measured anchor ice accumulation~~s~~ densities between 300 and 700 kg/m^3 and showed that the density tended to increase with the flow velocity.

Kempema and Ettema.(2009, 2011) ~~Several studies~~studied anchor ice on the Laramie River, USA (~~e.g. Kempema and Ettema., 2009; Kempema and Ettema, 2011~~) and reported that daily anchor ice cycles (formation at night and release in the morning) can generate anchor ice accumulation thicknesses between 0.~~2~~ 2 and 0.~~3~~ 3 m with no apparent relation between crystal sizes and Froude number. They ~~observed~~examined the morphology of anchor ice accumulations and reported that large plate-like ice crystals exceeding 10 cm in length were most dominant. They also observed that these large crystals result from in situ growth of frazil crystals that become attached to the bed. While studying anchor ice rafting by sediments, they concluded that anchor ice release and associated ice rafting were diurnal events, which suggests that solar radiation was an important factor.~~They also~~ Kempema and Ettema (2013, 2016) used time-lapse images from an underwater camera to measure the growth of anchor ice crystals forming on ~~a~~ wedge-wire screens deployed on the river bed. ~~-~~They reported that anchor ice formation was initiated by the accretion of frazil disks followed by relatively rapid in situ ice growth. They observed ~~the morphology of anchor ice accumulations and reported that large plate-like~~ ice crystals ~~exceeding 10~~up to 3 cm ~~in length were most dominant and that disc-like crystals are rarely seen~~long with growth rates ranging between 1.0 to 4.0 cm/hr. They also measured anchor ice accumulation porosities between 42% and 68%. They observed that these large crystals result from in situ growth of frazil crystals that become attached to the bed. While studying anchor ice rafting by sediments, they concluded that anchor ice release and associated ice rafting were diurnal events, which suggests that solar radiation was an important factor.

Stickler and Alfredsen (2009) conducted a detailed study on anchor ice formation at three sites: two sites on unregulated rivers (Southwest Brook, Canada, and River Sokna, Norway), and one site on a regulated stream (River Orkla, Norway). They concluded that anchor ice formation is mainly due to frazil deposition and is dependent on the flow turbulence (i.e. Reynolds number) with no apparent correlation with Froude number. They reported that in low turbulence areas (median Reynolds number of ~ 10,000) anchor ice grew in the vertical direction with a soft texture and low densities (between 360 and 600 kg/m^3), smaller frazil crystals (<0.01 m), and thinner accumulation thicknesses (median of 0.04 m). In high turbulence areas (median Reynolds number of ~ 25,000), anchor ice grew in both the vertical and lateral direction with much higher densities (between 600 and 900 kg/m^3), larger particles (up to 0.1 m) and larger accumulation thicknesses (median 0.07 m). Anchor ice release was only observed when the water temperature increased above zero and when shortwave radiation (direct sunlight) reached the bed.

Dubé et al. (2014) investigated the characteristics of anchor ice accumulations on the Montmorency River, Canada using thin sections analysis and computed axial tomography (CAT) scans of the collected anchor ice samples. Elongated columnar ice crystals were observed only in ice dam samples and disk-shaped ice crystals were observed in both ice dam samples and submerged anchor ice samples. In both cases, the crystals showed grew preferentially perpendicular to the flowgrew preferentially perpendicular to the flow. Their results also suggested that in situ growth of disk-shaped ice crystals was the dominant process for the formation of anchor ice and ice dams. They reported individual ice crystals between 3 and 6 cm in length with mean accumulation porosity between 38 and 44%.

Jasek et al. (2015) and Jasek (2016) monitored anchor ice release in the Peace River, Canada. They showed that anchor ice formation and release caused significant fluctuations in discharge and water levels, which caused ice cover instability and consolidation, and consequently freeze-up jams. Their observations showed that anchor ice release appeared to be mainly due to hydraulic effects, rather than thermal influence of the sun. Acoustic scanning of the river bottom indicated length to thickness ratios of ~ 24:1 for the anchor ice patches on the bed. They estimated ice coverage to be ~ 70% for a reach of over 200 km in length.

Nafziger et al. (2017) studied three streams in New Brunswick, Canada (2 unregulated and 1 regulated) and 161 anchor ice formation/release events were observed using time-lapse photographs from the shore. A correlation was found between the increase in water depth (stage) during the formation of an anchor ice event, and the corresponding accumulated freezing degree hours of air temperature. Although there were no direct measurements of growth of anchor ice accumulation, the “trend” of the increase in water levels showed good agreement with the laboratory growth rates reported by Kerr et al. (2002). On days with a net heat gain at the water surface and air temperatures > -15°C, 98 % of anchor ice accumulations completely released, which indicates a strong thermal control on anchor ice release.

As discussed above, previous field and laboratory studies have provided considerable insight into the formation, release, and properties of anchor ice but there are still considerable gaps in our knowledge. For example, the relative importance of frazil deposition versus in situ growth, mechanical versus thermal release and single versus multi-day cycles. However, one of the most critical gaps is that the anchor ice growth rates and mechanisms observed in the laboratory have never been confirmed in the field. The primary goal of this study was to address this gap by making direct measurements of anchor ice growth in the field. For this purpose, a custom-built underwater imaging system (camera and lighting) was deployed on the North Saskatchewan River in Edmonton. The imaging system was able to capture for the first time high-resolution digital time lapse images of anchor ice formation, growth and release mechanisms. This paper describes the deployments of the imaging system, results from the continuous measurements of anchor ice processes, and the effect of ambient hydro-meteorological conditions on these processes.

3 Study Site and Methods

3.1 Study site

The North Saskatchewan River, Canada, (length ~1300 km; mean annual discharge of 245 m^3/s at the downstream end at Prince Albert) is a glacier-fed, regulated river that flows east from the Canadian Rockies (1,800 m above sea level) across Alberta (720 m above sea level at Edmonton), to central Saskatchewan (Kellerhals et al., 1972). The river reach within Edmonton is irregularly meandering with many point bars and side channel bars. It ranges in depth between 1 and 3 meters, and between 150 to 250 meters in width (Gerard and Andres, 1982). The bed material is composed of glacial till and alluvial sands and gravels (Kellerhals et al., 1972). The winter discharge is largely controlled by the outflows from the Bighorn and Brazeau dams in the upper part of the basin and the average daily winter discharge at Edmonton is 126 m^3/s (Hicks, 1997). During winter, hydropeaking power generation at the two dams typically causes water level fluctuations of 30 to 50 cm at the study site. Freeze-up on the North Saskatchewan River in Edmonton can start as early as mid-October and a complete ice cover can form as late as the end of December. Figure 1 presents a map showing the study site on the North Saskatchewan River in Edmonton. Measurements of anchor ice were conducted at the City of Edmonton Quesnell Bridge (53°30′20″N 113°33′60″W) during freeze-up season (October to December) of 2018. The river in this reach has a slope of ~ 0.0002 and a width of ~ 200 m. This site was selected for its accessibility and because anchor ice has been observed forming in this reach during previous studies (e.g. Kalke et al., 2017).

3.2 Instrumentation

In order to capture high-resolution photographs of anchor ice properties in the field, an underwater imaging system and artificial substrate were designed and built as shown in Fig. 2. The imaging system consisted of a 36-megapixel Nikon D800 digital single-lens reflex (DSLR) camera (equipped with a Micro-Nikkor 35 mm f/1.8D lens) coupled with a Nikon SB-910 Speedlight flash. Both the camera and the flash were contained in underwater housings which were mounted side-by-side on a MiniTec aluminum rail. The imaging system was secured in a 100 cm long, 50 cm wide, and 20 cm high PVC frame. The aluminum rail was designed to release from the frame using two 20 cm high handles and a pivot hinge assembly. This feature allowed the rail to be lifted out of the frame so that images could be examined and batteries changed without removing the entire system from the river. The frame was equipped with two ten-pound weights to help anchor the system to the river bed. In order to prevent frazil and anchor ice from forming on the camera and flash lenses, a 10 m long pipe heat trace cable was wrapped around both underwater housings and then covered with insulating bubble wrap. The heat trace cable was extended using a 30 m power cord laid out along the river bed and connected to a Subaru R1700i gas generator secured on the river bank. The generator needed to be filled with gas every ~7 to 8 hours.

An artificial substrate was constructed and bolted to the imaging system frame as shown in Fig. 2. Although imaging anchor ice formation directly on the natural river bed would be ideal, it is very difficult to pre-adjust the camera settings and lightings to acquire clear images of the forming anchor ice. However, using a constructed substrate allowed us to conduct preliminary laboratory experiments to adjust these settings in a controlled environment. In addition, a constructed substrate offered the opportunity to observe multiple anchor ice events growing on an identical substrate, eliminating variation in bottom sediment properties as an experimental variable. Lastly, it also allowed us to closely examine and photograph any anchor ice deposits that had not released once the system was removed from the water. To make the constructed substrate as similar as possible to the natural river bed, bed material was sampled from the river at the deployment site in early October 2018. The bed samples were oven dried and sieved in the University of Alberta geotechnical lab. ~~Gravels/boulders~~Sediment particles that were greater than 3.8 cm (1.5 inch) in size were used for the substrate. The substrate materials were hand-picked so that they have one relatively flat side and they ranged in size from 3.8 cm to 12.5 cm which is classified ~~between~~as very coarse pebble gravel ~~and~~to fine cobble gravel (Valentine, 2019). The gravel~~/boulders~~ particles were then glued (with the flat side facing down to increase contact area) to a 50 by 50 cm wide plywood base. Multiple 2.5 cm diameter holes were drilled into the base to reduce buoyancy forces on the substrate.

Initial imaging settings (including ISO, aperture, focus and duration of the flash pulse) and the distance between the substrate and the lens face were determined in the laboratory by immersing the system in a tank of tap water. These camera settings and the setup configuration were modified over the course of the field deployments to improve image quality and increase the camera battery life. These modifications included: decreasing the distance from the camera housing window to the in-focus bed material from 60 cm to 40 cm; adding a 25 mm extension tube to the camera lens; changing the underwater camera housing from a clear Ikelite D800 housing to a coated aluminum Aquatica AD800 housing; and increasing the image sampling interval from 30 seconds to 5 minutes. Adding the extension tube and moving the substrate closer resulted in a field of view in the images of 34 by 18 cm as opposed to 45 by 30 cm for the original configuration. Increasing the image sampling interval extended the camera battery life from about 6 hours to 24 hours.

In addition to photographing anchor ice, the water temperature was measured to investigate the effect of temperature variations on anchor ice formation and release. Measurements were made using two RBR SoloT (accuracy ±0.002°C) temperature loggers sampling every 5 seconds: one mounted on the substrate and another attached to the top of the frame at 20 cm above the bed (see Figure 2). The anchor ice imaging system was deployed a total of four times during the freeze-up season. During each field deployment, the instruments were carried from the south bank of the river and installed on the river bed. For the first three deployments, the system was installed 15 to 20 m from the south shore (between the right bank and the first Quesnell Bridge pier) where the water depth ranged between 0.6 and 0.7 m at the start of the deployments (see Fig. 1). For the last deployment, the instruments were lowered from the border ice ~ 100 m upstream of the bridge and ~ 30 m from the south shore in a water depth of 1.6 m.

Meteorological data was downloaded from the Alberta Climate Information Service (ACIS) website. The closest weather station (approximately 2.0 km southeast of the study site, see Fig. 1) was the “Edmonton South Campus UA” station (Climate ID 3012220) which provides hourly weather data for the air temperature, solar radiation, wind speed and direction, rainfall/snowfall depth and relative humidity. Real-time hydrometric data for North Saskatchewan River at Edmonton was obtained from Water Survey of Canada gauge #05DF001 in a 5-minute interval. The gauge is located approximately 10.7 km downstream of the study site (Fig. 1).

4 Data Analysis

A careful examination of the images showed that the imaging system was able to capture individual anchor ice crystals growing on the artificial substrate and also the thickness of anchor ice accumulation. Therefore, the images were processed to primarily estimate these two quantities. All of the captured anchor ice images were processed in two steps. First, the images were enhanced using image processing software (BatchPhoto Pro ®). The enhancements included: stamping the date/time when the image was taken, auto adjusting the contrast, reducing the hue, increasing the saturation, increasing the lightness, and reducing the noise in the images. These enhancements corrected for the continuous change in ambient lighting and flow turbidity over the course of a single deployment.

Second, the enhanced images were imported into MATLAB ® and the edge of anchor ice crystals and the anchor ice accumulation thickness was manually tracked as a function of time using the image processing toolbox. For the crystal growth measurements, the images were visually examined to identify a number of crystals (typically between 1 and 4 crystals) that were clearly visible in consecutive images. Then the pixel coordinates of the edge of each identified crystal were manually tracked and extracted from the series of images. The pixel distance between the edge of the same crystal on successive images was scaled by using the in-focus size of the substrate material. The total length of the crystal was then calculated to estimate the growth of the accumulation with time. A processed image showing the individual crystals forming on the substrate is presented in Fig. 3a. The anchor ice accumulation thickness was measured by manually tracking multiple points across the top of the accumulation in each image. The average accumulation thickness was calculated for each image by averaging these manually tracked points across the width of the image. A processed image showing anchor ice accumulation atop the substrate is shown in Fig. 3b.

There are three possible sources of uncertainty in the anchor ice measurements that have been identified: (1) the camera resolution, (2) errors in identifying the same crystal is consecutive series of images, and (3) errors associated with the assumption that the scaling factor used to convert pixel dimensions to real dimensions (i.e. centimeters) was a constant. The camera resolution is 36 megapixels which resulted in a pixel size of approximately 40 μm and therefore, errors related to camera resolution are negligible. When tracking the growth of individual crystals, each pair of consecutive images were printed and overlapped (after applying a percentage of transparency to one image in MATLAB) to confirm that the same crystal was identified throughout a series of images. This procedure eliminated -any possible errors identifying individual crystals (Stage 1). The third source of uncertainty is due to the fact that objects of interest in the image (crystals or the top of an accumulation) may be located closer or farther away than was assumed when calculating the image scaling factor. Laboratory tests showed that the in-focus section of the substrate was ~40 cm away from the face of the lens and this was assumed to be the object distance (distance from an in-focus object to the camera lens) when calculating the scale factor. During Stage 2, the top of frazil accumulations were typically clearly visible in the images (e.g. see Fig. 3b) but the object distance could not be estimated accurately in each image. This is due to the fact that the clarity of the water was reduced by the presence of both suspended frazil and sediment. As a result, the images were always blurry (e.g. see both images in Fig. 3) making it impossible to know which features or objects in the image were in-focus and therefore located at an object distance of ~40 cm. It is estimated that the crystals or the top of accumulations could be ± 10 cm closer or farther away from the lens than the 40 cm (the object distance), since the edge of the substrate facing the camera was 30 cm away from the lens, and the camera flash could not illuminate beyond 50 cm away from the camera. Therefore, this would produce ae maximum error of ± 25% in measured crystal and accumulation dimensions and in the computed growth rates.

5 Results

5.1 Synopsis of Field Deployments and Anchor Ice Events

Figure 4 presents time series of the air temperature and the river stage measured from 1-Nov-2018 to 31-Dec-2018. The first ice pan was observed in the river on 7-Nov-2018 and the river was completely ice covered on 23-Dec-2018. The freeze-up season lasted almost 46 days and was one of the longest in recent years. During freeze-up, the weather forecast was monitored and the dates of the deployments were determined based on when supercooling of the river was expected to occur and the availability of the research team. The anchor ice imaging system was deployed a total of four times (referred to as DEP-1 to DEP-4) during the 2018 freeze-up season as highlighted in Figure 4. Table 1 summarizes the camera settings and the duration and timing of each deployment.

Figures 5 to 8 present time series of the measured air temperature ~~and~~ , water temperature~~s~~, solar radiation, river stage, and anchor ice thickness during the field deployments DEP-1 to DEP-4, respectively. Prior to deployments DEP-1 and DEP-2, the air temperature was above zero and dropped to -10 and -15°C, respectively during the deployments, and frazil pans more than 30 cm thick were observed passing by the deployment site. For DEP-1 the instruments were deployed at 20:00 on 11-Nov-2018 and were retrieved at 8:00 on 12-Nov-2018; a duration of 12 hrs. The recorded anchor ice event during DEP-1 was labelled as Event A (see Figure 5). During this event, anchor ice started to form on the substrate at 21:00 on 11-Nov-2018 shortly after the deployment started. Unfortunately, the camera stopped working from 1:50 until the battery was replaced at 4:30 on 12-Nov-2018. During this event, the water was continuously supercooled at approximately a constant temperature of -0.009 °C. When the instruments were retrieved at 9:00 on 12-Nov-2018, anchor ice was still attached to the substrate and therefore, no images of anchor ice release were captured during this event. The quality of the images captured during this event did not allow the tracking of individual crystals, but the top of the anchor ice accumulation was visible in the images. Figure 9 presents a photograph of the substrate after Event A showing a significant accumulation of anchor ice during this 12-hour event.

DEP-2 started at 18:00 on 15-Nov-2018 and ended at 12:00 on 17-Nov-2018, lasting for 40 hours (see Fig. 6). Although DEP-2 lasted two nights, anchor ice did not form during the first night because the water was above 0°C. During this event, a classic supercooling curve was observed, which reached a maximum supercooling temperature of -0.09°C at approximately 17:00 on 16-Nov-2018 and then warmed up to an average residual temperature of approximately -0.02°C. Anchor ice crystals started to form on the substrate at ~16:30 on 16-Nov-2018 just before the water reached its maximum supercooling and shortly before the solar radiation reached zero W/m^2. The camera stopped working from 2:25 until 5:53 on 17-Nov-2018 when the camera battery was replaced. At about 6:40 the heat trace stopped working because the generator stalled and the lens was completely covered with ice. When the instruments were retrieved at 11:40, some anchor ice was still attached to the substrate but it seems that the majority of the detected anchor ice in the images had released sometime after 6:40 and prior to retrieval. Although this deployment experienced several instrument failures, it was possible to track individual crystal growth and the thickness of anchor ice accumulation in the images.

After DEP-2, the air temperature stayed relatively warm until 1-Dec-2018 when the temperature dropped below zero. DEP-3 started at 16:00 on 3-Dec-2018 when the air temperature decreased from -5 to -15°C and lasted 43 hours until 12:00 on 5-Dec-2018 when the instruments were retrieved (see Figure 7). Events C and D were both captured during DEP-3. During these two events, the camera and the generator did not encounter any issues and worked throughout the entire deployment period. Anchor ice started to form on the substrate at 16:40 and 17:55 shortly after the solar radiation reached zero W/m^2 and released the next morning at 8:20 and 7:15 shortly before sunrise at 8:30 for Events C and D, respectively. During this deployment, the water was constantly supercooled at about -0.009°C except when it decreased to -0.018°C around the time of the release of Event C. Images from Events C and D were used to extract anchor ice crystals growth and thickness of anchor ice accumulation.

After DEP-3, the air temperature gradually warmed again but rafts and ice pans were still observed in the river. On 15-Dec-2018 the temperature dropped from above 0 to -10°C and the river started to stage-up due to higher surface pan concentrations and possibly multiple bridging locations downstream of the study site. DEP-4 lasted for 49 hours from 16:30 on 15-Dec-2018 until 17:30 on 17-Dec-2018 (see Fig. 8). During this deployment, the water was constantly supercooled at about -0.01°C. Events E and F were both captured during DEP-4. Anchor ice started to form on the substrate at 16:45 and 16:25 (immediately after the solar radiation reached zero W/m^2) and released in the afternoon of the next day at 13:20 and 14:40 for Event E and F, respectively. It was believed that these events lasted longer because the instruments were deployed in a much deeper location (1.6 m deep as opposed to ~ 0.6 m for the previous deployments) which decreased the effect of heating by solar radiation. Due to higher turbidity images from Events E and F were only used to extract the thickness of anchor ice accumulation since it was not possible to distinguish individual crystals in the images.

At the end of each deployment, after the retrieval of the instruments from the river, images of anchor ice that had not released from the substrate were taken (e.g. Fig. 9). From these images, three distinct anchor ice crystal shapes were observed on the substrate as shown in Fig. 10. These shapes are: (a) curved needle crystals that grew on the surface of the bed material from the contact edges between adjacent gravels towards the centre of the gravel from all sides; (b) platelet crystals that grew starting in the interstitial spaces between gravel particles and then grew vertically away from the gravel, typically angled upstream; and (c) disk shaped crystals that look like typical suspended frazil ice crystals that attached to the substrate. It is clear in Fig.10 that within each anchor ice accumulation, different crystal shapes are present which demonstrates the complexity that is commonly observed in anchor ice accumulations.

5.2 Anchor Ice Formation, Growth and Release

The processed images from each anchor ice event were combined in time lapse videos to help visualizing the results. An example of such videos for Event C is available for download at https://doi.org/10.7939/DVN/6X5ATL (Ghobrial and Loewen, 2019). Using these videos, the process of anchor ice formation, growth and release was separated into four stages, namely: Stage 1: initiation by in situ growth, Stage 2: transitional phase, Stage 3: linear growth, and Stage 4: release phase. For illustration purposes, these stages are labelled on the time series results of anchor ice thickness measured during Event C as shown in Fig. 11. The results of all anchor ice events are summarized in Table 2. Initiation of anchor ice by in situ crystal growth (Stage1) was only observed in Events B, C, and D (see Fig. 6c and 7c). During Stage 1 individual anchor ice crystals started to grow off the substrate typically angled in the upstream direction of the flow. It is of interest to examine the rate of anchor ice crystal~~s~~ growth observed during these events. For this purpose, a total of nine crystals were tracked, four crystals from each of Events B and C, and one crystal from Event D. The growth of the leading edge of these crystals is plotted against time in Fig. 12. Note that the time scale for each crystal length measurements was referenced to when the individual crystal first appeared in an image. The individual crystals grew at ~~an~~ approximately linear rates ranging from 0.9 to 2.4 cm/hr with an average of 1.7 cm/hr. This stage lasted between ~ 1.5 to 3.0 hours (typically between 18:00 and 21:00). At the end of Stage 1, the crystals ranged between 2.8 cm and 7.7 cm in length.

Stage 2 is a transitional period when individual crystals came in contact with each other and were not easily distinguished in the photographs. During this stage, the surface of the anchor ice started to become flattened by the flow due to the increased drag force and then continued to grow through the deposition of suspended frazil crystals and flocs and/or further interstitial crystal growth. This stage was only distinguishable during the three events B, C, and D when in situ crystal growth was observed. This stage lasted for ~4 hours (typically between 21:00 and 1:00). In Stage 3 the deposition was already flattened out and the anchor ice accumulation had a distinct upper surface which continued to grow upwards at an approximately constant rate due to frazil deposition. This stage lasted for ~8 hours (typically between 1:00 and 7:00). For Events A, E, and F frazil deposition appeared to be the initiation mechanism of anchor ice formation and therefore Stage 1 was not observed during these three events. Consequently, for analysis purposes, the growth of the anchor ice accumulation during Stage 2 and 3 (combined) is plotted in Fig. 13 for all six events. The time scale for each event was referenced to when anchor ice first appeared in the images for Events A, E, and F; but for Events B, C, and D the start time was referenced to when Stage 1 ended. The average rate of accumulation growth during all events ranged between 0.3 and 0.9 cm/hr with an average of ~ 0.6 cm/hr (Table 2). At the end of Stage 3 the anchor ice accumulation thickness due to frazil deposition only was between 5.3 and 9.6 cm.

Stage 4, the release of anchor ice, was recorded for Events C, D, E and F but not for Events A and B due to equipment malfunction or due to retrieval prior to the release. Three modes of anchor ice release were observed in the data: lifting, shearing, and rapid release. During the release of Events C and E, the entire anchor ice accumulation was observed lifting up away from the substrate until it suddenly completely released. This mode lasted ~20 and ~100 min with a lifting rate of 9.0 and 3.3 cm/hr for Events C and E, respectively. During Event D, consecutive layers of accumulation were sheared off with the top layer releasing first followed by the bottom layer. This release mode lasted ~ 20 min. The release of the entire accumulation during Event F occurred in less than 5 minutes (i.e. the time between consecutive images) and therefore no lifting or shearing was observed.

6 Discussion

Three stages of anchor ice growth very similar to those reported by Kerr et al. (2002) were observed for the first time in the field in this study using time-lapse photographs. 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). It should be noted that Kerr et al. (2002) did not report observing in situ crystal growth and attributed the faster growth in Stage 1 to only frazil deposition. Qu and Doering (2007) did not directly observe in situ thermal growth in their anchor ice images but did conclude that it occurred in their laboratory experiments based on careful analysis of water temperature time series. Kempema and Ettema (2009) studied anchor ice crystal morphology on a small riffle-and-pool stream and collected anchor ice samples that were comprised of large blade-shaped crystals up to 5 cm in length (see their Fig. 1). They concluded that these larger crystals were formed by in situ growth of suspended frazil crystals that had become attached to the bed. Furthermore, they wrote that anchor ice formed initially by adhesion of frazil ice crystals to the bed and subsequent growth occurred by a combination of frazil accretion and in situ growth. It is unclear if they are referring to the adhesion of a relatively small number of suspended frazil ice crystals to the bed that subsequently acted as nucleation sites for the growth of large crystals,. Oor if they are referring to the adhesion of a sufficient number of crystals that a layer of measureable thickness is initially formed and that in situ growth occurred within this layer. Their description of anchor ice formation is certainly consistent with events A, E and F in which only frazil deposition was observed. However, for events B, C and D in which in situ growth of large crystals was initially observed there is some uncertainty. Initial adhesion of suspended frazil ice crystals to the bed prior to the start of large crystal growth was not observed in the time-lapse images but this could be because the suspended crystals were much too small to be visible. Therefore it is possible that the first step in anchor ice formation is the adhesion of suspended frazil crystals to the bed and in this case it would follow that some of these crystals could then act as nucleation sites for the large crystals that were observed growing on the bed in this study. This process would also be consistent with Kempema and Ettema's (2009) description of their field observations.

The initial or Stage 1 crystal growth rates measured in this study ranged from 1.3 to 2.0 cm/hr. and this is within the range of 0.4 to 2.3 cm/hr McFarlane et al. (2016) reported by McFarlane et al. (2016) for growth rates between 0.4 and 2.3 cm/hr of for dendritic frazil ice crystals observed in a sequence of images of a frazil floc trapped between two cross-polarizing filters at the same field site. Initial growth rates of anchor ice accumulations in a laboratory channel were estimated from the slopes of the curves plotted in Fig. 19 from Kerr et al. (1997) and these varied from approximately 1.7 to 2.8 cm/hr. Kempema and Ettema (2013, 2016) observed anchor ice growing on wedge wire screens in the Laramie River and plotted crystal growth as a function of time (e.g. see ~~their~~ Fig. ~~8, 9 and 10~~5 in Kempema and Ettema, 2016). The initial growth rates estimated from these plots ranged from approximately 1.0 to 4.0 cm/hr. ~~However, it is uncertain if wedge wire screens accurately model the growth of anchor ice on the river bed. The wedge wire screens were mounted above the bed where velocities would be higher and it is possible that the slightly higher observed growth rates were due to higher turbulent heat transfer rates associated with these elevated water velocities. The~~ In summary, the reported field and laboratory measurements of anchor ice crystal growth ~~on the channel beds~~ range between~~suggest that initial growth rates range from~~ approximately 1.0 ~~to~~ and ~~3~~4.0 cm/hr. The differences in observed crystal growth rates ~~can be due to the several reasons~~were likely due to local variations in ~~such as the local~~ turbulent flow properties~~turbulence level~~, heat loss rates, and/or the characteristics of the substrate on which crystals grew. It is important to note that even on the same substrate, and during the same time interval, individual anchor ice crystals grew at different rates as shown in Fig. 12 for event C. In this case the different growth rates ~~This~~ might be because crystals ~~originated from different parts~~growing at different positions on the substrate and in different orientations relative to the flow ~~of the substrate and as a result, they were~~would be exposed to different flow conditions.

The time lapse images of anchor ice during Stage 2 and 3 indicate that the growth of the accumulations was mainly due to frazil deposition. It is possible that further in situ crystal growth in the interstitial spaces between the deposited frazil crystals occurred and this would increase the accumulation density and strengthen the bond between crystals. The rate of growth of anchor ice accumulation during Stage 2 and 3 ranged between 0.3 and 0.9 cm/hr. This rate is in agreement with the laboratory measured rates of 0.4 to 0.8 cm/hr reported by Kerr et al. (2002) and 0.3 to 0.7 cm/hr reported by Doering et al. (2001). It is interesting to note that in this study the average rate of crystal growth (Stage 1) of 1.7 cm/hr was ~ 3 times the average rate of the accumulation growth due to deposition of frazil (Stage 2 and 3). In order to examine the effects of heat loss on the growth rate of anchor ice, following Kerr et al (2002), the thickness of accumulation from all the events during Stage 2 and 3 were plotted against the cumulative degree hour of freezing air temperature as shown in Fig. 14. The linear rates of growth observed in the field ranged between 0.05 and 0.12 cm/°C-hr compared to 0.02 to 0.05 cm/°C-hr observed in Kerr's experiments. Nafziger et al. (2017) plotted the rise of water level due to anchor ice formation against the cumulative degree hours of freezing and also found that most of the observed events have rates of growth higher than 0.05 /°C-hr which is in agreement with this study.

Total anchor ice thicknesses measured in this study (at the end of Stage 3) ranged between 6.1 and 15.4 cm. This range is consistent with the ranges reported in some previous studies, e.g.: 3 to 17 cm by Hirayama et al. (1997), 20 to 30 cm by Kempema et al. (2001), and 7 to 10 cm by Stickler and Alfredsen (2009). The crystal~~s~~ sizes observed in this study ranged between 2.8 cm and 7.7 cm and are in agreement with previous field studies, e.g.: 3 to 6 cm by Dubé et al. (2014), and up to 10 cm by Kempema and Ettema (2011). However, several studies do report substantially thicker accumulations. Tremblay et al. (2014) reported thicknesses ranging from 0.18 to 0.46 m in a small river (width 6-12 m) and Evans et al. (2017) reported accumulations up to ~0.9 m thick, using side-scan sonar in a much larger river (width 220-440 m). During this study, the research team observed anchor ice accumulations projecting out of the water surface in water depths of 1.6 m or greater at the deployment site. Also, several holes augered through the border ice showed that the bottom of the border ice was in contact with and possibly supported on the underlying anchor ice accumulation in water depths up to ~1.5 m. The sources ofof tThe origins of theseose thick deposits could includes local anchor ice growth, accumulation of floating frazil slush, stacking of released anchor ice from upstream, or a combination of any of these phenomena. If we only consider anchor ice growth, Aat an average growth rate of 0.6 cm/hr it would take 267 hours for 1.6 m of anchor ice to accumulate. If anchor ice grows only during ~12 hours a day of supercooling, about 22 days of growth would be required to accumulate 1.6 m. Also, several holes augered through the border ice showed that the bottom of border ice was in contact with and possibly supported on the underlying anchor ice accumulation in water depths up to ~1.5 m. Nafziger et al. (2017) also observed this phenomenon. Anchor ice accumulations this thick are unusual in this reach of the North Saskatchewan River but the freeze-up season was much longer in 2018 than is typical. Ice pans first appeared on the river Nov. 7, 2018 and a solid ice cover was not formed until Dec. 23, 2018 a total duration of 46 days approximately twice as long as the typical duration. Evidently this much longer freeze-up duration might have enabled much thicker accumulations of anchor ice to form than is typical.

Four of the six anchor ice events observed in this study started within 0.5 hr of sunset and the remaining two events started 1.6 and 4.3 hr after sunset. This is consistent with what would be expected for diurnal anchor ice events that begin in the late afternoon or evening. At this time of day the combined effect of decreasing shortwave solar radiation and lower air temperatures typically leads to an increase in the net heat flux from the water to the atmosphere that initiates anchor ice formation. Events C and D occurred in shallow water (~0.6 m) and released the following morning at 8:20 and 7:15 or 0.2 and 1.3 hours prior to sunrise, respectively. Events E and F occurred in deeper water (~1.6 m) and released in the afternoon at 13:20 and 14:40 or 4.5 and 6 hours after sunrise, respectively. In all four cases the water remained supercooled at the observed residual temperature for the entire duration of each event indicating that there was no warming of the water detected by the temperature logger mounted on the substrate. The fact that release occurred while the water temperature remained constant and supercooled is evidence that release was not caused by the melting of the bond with the substrate due to warming water. However, it might be possible for the bond to melt due to heat transfer from the sediments with no observable change in the water temperature. Evidence for the role of shortwave solar radiation in the release is inconclusive since two accumulations released prior to sunrise and two near mid-day. The fact that the two accumulations in deeper water released later in the day suggests that solar radiation might have played a role in the release since this effect would take longer to penetrate deeper water but this is not conclusive evidence. The air temperature at the time of release for Events B, C, D and E was -10, -9.7, -

5.0 and -0.5°C, respectively. This is in agreement with Nafziger et al. (2017) who reported that most of the anchor ice release events they observed occurred when there was a positive heat flux to the water and the air was warmer than -15°C.

The possibility that mechanical forces triggered the release was also considered. Buoyancy and hydrodynamic forces always play some role in anchor ice release since they are always present. This can be illustrated by considering two limiting cases. In the first case the ice-substrate bond is weakened by thermal effects and one or both forces lifts or shears the accumulation off the bed. This would be characterized as thermal release since it was thermal radiation and/or heating that triggered the release. In the second case the strength of the ice-substrate bond remains constant and the magnitude of one or both forces increases triggering release. This would be characterized as mechanical release. In some cases both the strength of the ice-substrate bond and the magnitude of the forces may be varying and then release could be triggered by both a weakening of the bond and an increase in one or both of the forces. In this study the four accumulations (Events C, D, E, F) grew to thicknesses that ranged from 6.1 to 15.4 cm and then released. Nafziger et al. (2017) estimated the strength of the anchor ice-substrate bond using an equation proposed by Malenchak (2011) and by assuming that the anchor ice accumulation released solely due to buoyancy forces. In order to make similar calculations we assumed the anchor ice density varied from 300-700 kg/m^3, ice density was equal 917 kg/m^3, substrate diameter ranged from 0.038 to 0.125 m (range of rock sizes used in the constructed substrate) and the accumulation thickness varied from 0.061 to 0.154 m (the range of observed thicknesses). This method gave estimates of the anchor ice-substrate bond strength that ranged from 18 to 111 N/m^2 which is comparable to Nafziger et al.'s (2017) values that ranged from 45 to 138 N/m^2.

It is difficult to quantitatively assess the role of hydrodynamic forces in the release of the four events since the only information available is the approximate local depth and the data from the Water Survey of Canada gauge (#05DF001). The gauge data for events C and D does not appear to be ice affected with water levels varying from approximately 3.15 to 3.45 m due to diurnal hydropeaking (see Fig. 7b). During events E and F, the water level was steadily rising from 3.16 to 3.71 m and did not follow the typical diurnal pattern indicating that the presence of ice was affecting the gauge (see Fig. 8b). The release of event C ~~anchor~~ coincided with a peak in the daily water levels of 3.38 m. The release of events D occurred during rising water levels 5-6 hours prior to the daily peak and the stage was 3.45 m. During events E and F the water levels were also rising (see Fig. 8b) likely due to a combination of hydropeaking and backwater effects related to ice congestion downstream and release occurred at a stage of 3.36 and 3.70 m, respectively. Therefore, all four anchor ice events that were observed releasing did so when water levels were rising or were approaching the daily maximum. This may indicate that hydrodynamic forces played a role in the release of these anchor ice accumulations, but it is difficult to conclude this with any certainty.

The rate of anchor ice growth is currently calculated in most river ice process models using the following equation,

$$\frac{dh}{dt} = \frac{\gamma C_v}{(1-e_a)} + \frac{\phi_{wi}}{\rho_i L_i (1-e_a)} \quad (1)$$

where h is the anchor ice thickness, t is time, γ is the frazil accretion rate to the bed, C_v is the volumetric concentration of suspended frazil, e_a is the porosity of anchor ice, ρ_i is the density of ice, L_i is the latent heat of ice and ϕ_{wi} is the net rate of heat transfer from the ice to the water (Shen et al., 1995). Using the average rates of growth measured in this study we can assess a realistic range for the parameters used in Eq. (1). The first term on the ~~right hand~~right-hand side models growth via frazil deposition and the second term models in situ growth and decay. There are two variables (C_v and ϕ_{wi}) to be predicted at each time-step and four parameters (e_a, ρ_i, L_i and γ) to be set to constant values in this equation. The density and latent heat of ice are typically assumed to be 917 kg/m^3 and 334 kJ/kg, respectively. The porosity of anchor ice samples collected in the field have ranged from 0.38 to 0.56 (Dubé et al., 2014; Jasek, 2016). The anchor ice samples collected in those two studies were either firm enough to maintain their structural integrity when removed from the water or were taken from released anchor ice pans. Newly formed anchor ice accumulations likely have higher porosities because they often do not maintain their structural integrity when sampling is attempted (Dubé et al., 2014). The porosity of frazil ice flocs has been estimated to be approximately 0.80 (Schneck et al., 2019) and this may represent a reasonable upper limit for the porosity of newly deposited anchor ice. Values for the accretion rate γ in the literature range from approximately 10^{-6} to 10^{-3} (Malenchak, 2011) and measurements of the volumetric concentration of frazil C_v reported in the literature vary from 10^{-6} to 10^{-2} (McFarlane et al., 2019). In this study growth rates due to deposition during Stages 2 and 3 were observed to vary from 0.3 to 0.9 cm/hr. Using the average growth rate of 0.6 cm/hr and assuming the porosity is 0.4, the value of the numerator γC_v is predicted to be 10^{-6}. This suggests that γ is likely not significantly less than ~10^{-4} m/s since this would require that C_v be significantly greater than ~10^{-2} which is not realistic.

During Stage 1 when in situ growth of anchor ice was observed the crystal growth rates ranged from 1.3 to 2.0 cm/hr. Using these values and porosities of 0.4 and 0.8, the resulting range in ϕ_{wi}, the net rate of heat transfer from the ice to the water, is estimated to be 220 to 1030 W/m^2. The higher heat flux corresponds to lower porosity and higher growth rate. Note that for the water to remain at a constant temperature, as was observed in this study, the heat flux from the ice to the water must be balanced by an equal net heat flux from the water to the air. The net heat flux from the water to the air can be estimated using a linear heat transfer equation with a heat transfer coefficient of 20 W/m^2 °C, a typical value for North American rivers (Beltaos, 2013). The lowest air temperature during the three anchor ice events when in situ growth was observed was -15°C and therefore the maximum net water-air heat flux would be estimated to be 300 W/m^2. This suggests that the lower limit of 220 W/m^2 is a more realistic estimate of the net ice to the water heat flux and therefore that the porosity of anchor ice formed by in situ thermal growth might be closer to 0.8 than 0.4.

7 Conclusions

The first continuous field measurements of the complete anchor ice cycle including, initiation, growth and release mechanisms were captured in this study ~~The first direct field measurements of anchor ice growth and release were captured in this study.~~ Three stages of growth similar to those reported by Kerr et al. (2002) were observed in the time-lapse images. A total of six anchor ice events were captured and growth due to frazil deposition and in situ growth was observed in three events and in the remainder only frazil deposition occurred. Anchor ice was observed releasing from the bed in three modes referred to as "lifting" of the entire accumulation, "shearing" of layers of the accumulation and "rapid" release of the entire accumulation~~lifting, shearing and rapid~~. The Stage 1 growth rates measured by tracking the growth of individual crystals on the substrate ranged from 1.3 to 2.0 cm/hr and these were comparable to rates observed in previous laboratory and field studies. The measured growth rates in Stage 2 and 3 due to frazil deposition varied from 0.3 to 0.9 cm/hr which were comparable to measurements made in two previous laboratory studies. It is worth noting that in this study significantly higher growth rates ranging from 0.05 to 0.12 cm/°C-hr were observed compared to the rates of 0.05 cm/°C-hr or less reported by Kerr et al. (2002).

All of the observed anchor ice accumulations began forming in the afternoon or evening between 16:30 and 21:00. The release of four of the accumulations was captured in the time-lapse images and occurred between 7:15 and 14:40. The two events in shallow water released just prior to sunrise and the two events in deeper water in the early afternoon. There is evidence that solar radiation, buoyancy and hydrodynamic forces may have all played some role in the timing of the releases. It does not seem likely that release was triggered directly by hydrodynamic forces because the water level and flow rate variations were not significant at the time of release. The fact that during all four events the water temperature remained supercooled at residual temperatures of approximately -0.01ºC is clear evidence that weakening of the ice-substrate bond by warming water was not a factor. It seems likely that the two events in shallow water released due to buoyancy since both released prior to sunrise. However, all that can be concluded regarding the release of the two deeper water accumulations is that buoyancy forces and/or solar radiation may have played a role. Clearly additional research investigating the factors that cause anchor ice release is required.

River ice process models currently use a semi-empirical equation to model anchor ice growth due to frazil deposition and in situ growth. This simple equation accounts for the two observed growth mechanisms and is based on sound physics combined with reasonable engineering approximations (Shen et al., 1995). Analysis of the term in the equation modelling frazil deposition leads to the conclusion that the frazil accretion rate γ must be greater than or equal to $\sim 10^{-4}$ m/s. Analysis of the second term that models in situ growth suggests that the porosity of newly formed anchor ice may be significantly larger than 0.4, the value that is typically used in model studies. Unfortunately, the field data gathered in this study did not enable an assessment of the accuracy of this equation. A first step in accomplishing this task would be to capture accurate simultaneous measurement of suspended frazil concentrations, anchor ice porosity and anchor ice growth rates under a variety of conditions. These would ideally be field measurements but due to the significant challenges of making these types of measurements in the field it might only be possible to perform them in the laboratory. This data would allow calculations of the frazil accretion rate and heat flux from the anchor ice by inverting the existing equation. This has the potential to improve application of the existing equation in two ways. First, it could provide an empirical method for specifying the value of the frazil accretion rate as opposed to the current practice which is to set the value based on judgement alone. Secondly, the estimates of the anchor ice to water heat flux could be used to improve the method used to compute it that uses the same equation used to predict the heat flux between the ice cover and the water. Finally, it is worth noting that recent progress improving and validating river ice process models by comparison to field data has been reported in the literature (Blackburn and She, 2019; Pan et al., 2020; Wazney et al., 2019).

Data availability.

Data are available from the authors upon request.

Author contributions.

TRG and MRL designed the apparatus and performed the field work together. TRG carried out the analysis and processing of the data, prepared the figures, and wrote the manuscript with review and contributions from MRL.

Competing interests.

The authors declare that they have no conflict of interest.

Acknowledgements.

We would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for supporting this project (RGPIN-2015-04670 and RGPAS 477890-2015) and Perry Fedun for his valuable technical assistance. We are grateful for that support.

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Tables

Table 1: Summary of field deployments and camera settings.

Deployments ID	DEP-1	DEP-2	DEP-3	DEP-4
Average local water depth (m)	0.6	0.6	0.7	1.6
Camera lens	35 mm lens	35 mm lens	35 mm lens + 25 mm extension tube	35 mm lens + 25 mm extension tube
Underwater camera housing	Ikelite D800	Ikelite D800	Ikelite D800	Aquatica AD800
Distance between lens and substrate (cm)	60	60	40	40
Field of view (width by height, cm)	45 by 30	45 by 30	34 by 18	34 by 18
Deployment start date (DD/MM/YY) and time (HH:MM)	11/11/18 20:14	15/11/18 19:27	03/12/18 16:26	15/12/18 16:44
Deployment end date (DD/MM/YY) and time (HH:MM)	12/11/18 8:54	17/11/18 11:41	5/12/18 11:44	17/12/18 17:30
Deployment Duration (hr)	12.7	40.2	43.3	48.8

Table 2: Summary of results for measured anchor ice events.

Event ID	Event A	Event B	Event C	Event D	Event E	Event F
Formation date (DD/MM/YY) and time (HH:MM)	11/11/18 21:00	16/11/18 16:30	3/12/18 16:40	4/12/18 17:55	15/12/18 16:45	16/12/18 16:25
Release date (DD/MM/YY) and time (HH:MM)	-	-	4/12/18 8:20	5/12/18 7:15	16/12/18 13:20	17/12/18 14:40
Event duration (hr)	-	-	15.7	13.3	20.6	22.2
Air Temperature Range (°C)	-5.6 to -10	-13 to -15	-7.4 to -10.5	-2.5 to -9.7	-1.7 to -9.9	-0.2 to -9.2
Water Temperature (°C)	-0.009	-0.03 to -0.088	-0.009	-0.009	-0.010	-0.010
Stage 1 average growth rate (cm/hr)	-	1.3	1.9	2.0	-	-
Stage 2&3 average growth rate (cm/hr)	0.6	0.4	0.8	0.9	0.3	0.4
Accumulation thickness (cm)	7.6	8.7	15.4	11.3	6.1	10.6
Stage 4: Release mechanism	-	-	Lifting	Shearing	Lifting	Rapid

Figures

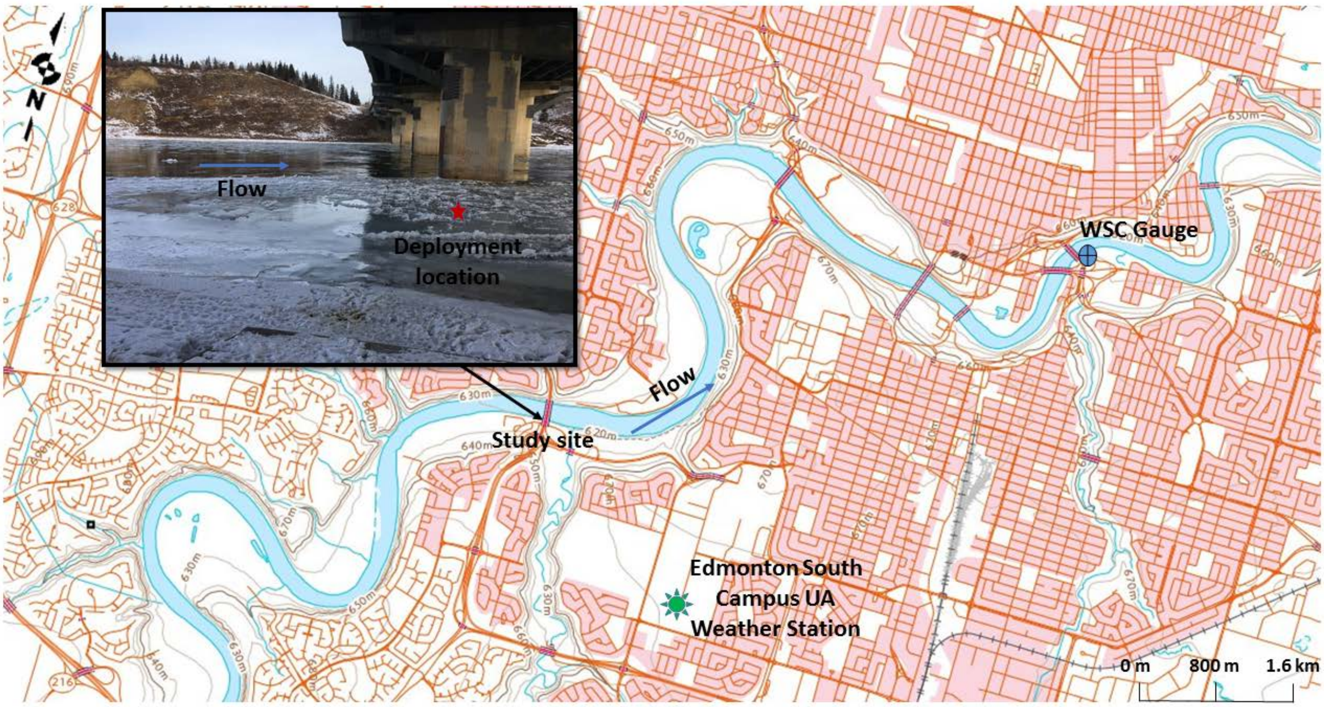

Figure 1: Map showing the study site on the North Saskatchewan River in Edmonton at the Quesnell Bridge (the base map was downloaded from the Atlas of Canada-Toporama website). The inset is a photo from the right bank looking north showing the deployment site under the bridge.

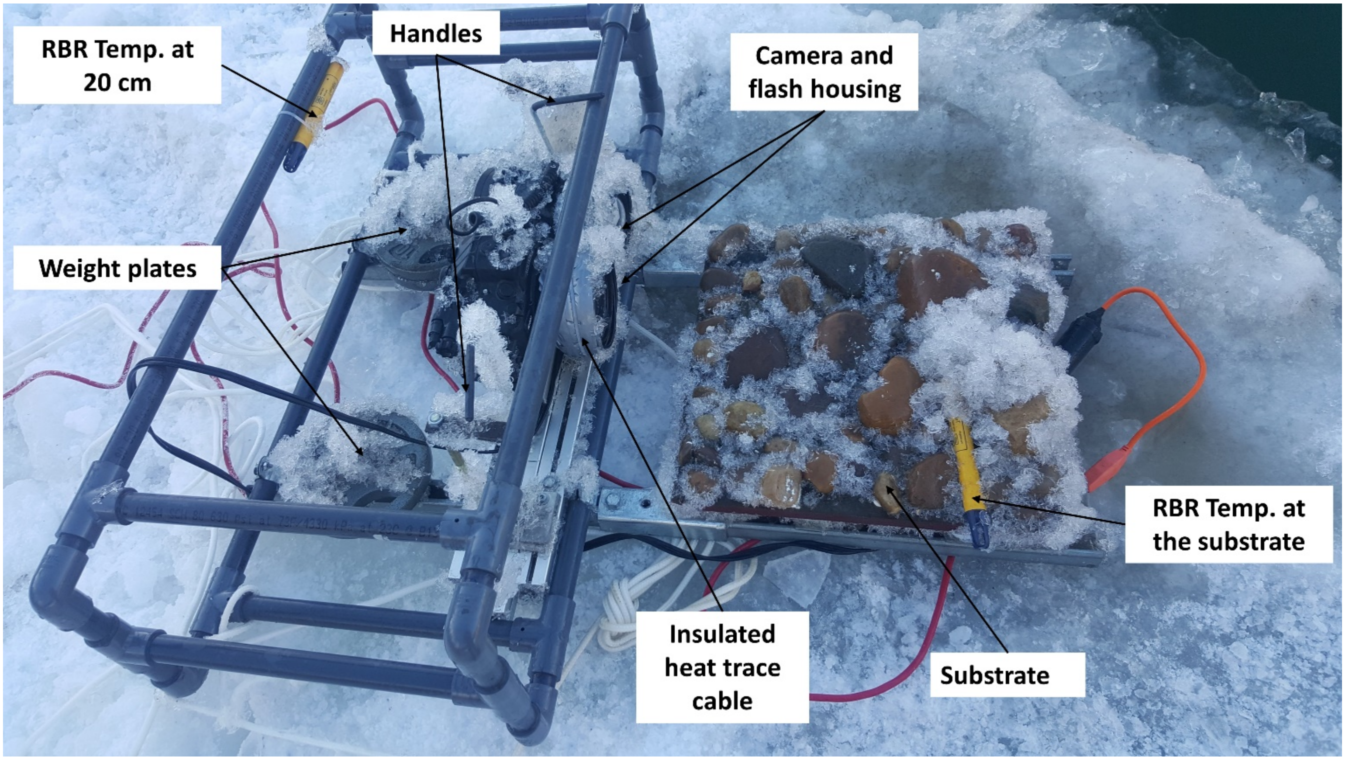

Figure 2: Anchor ice imaging system and artificial substrate after its retrieval from the river on Nov. 12th, 2018.

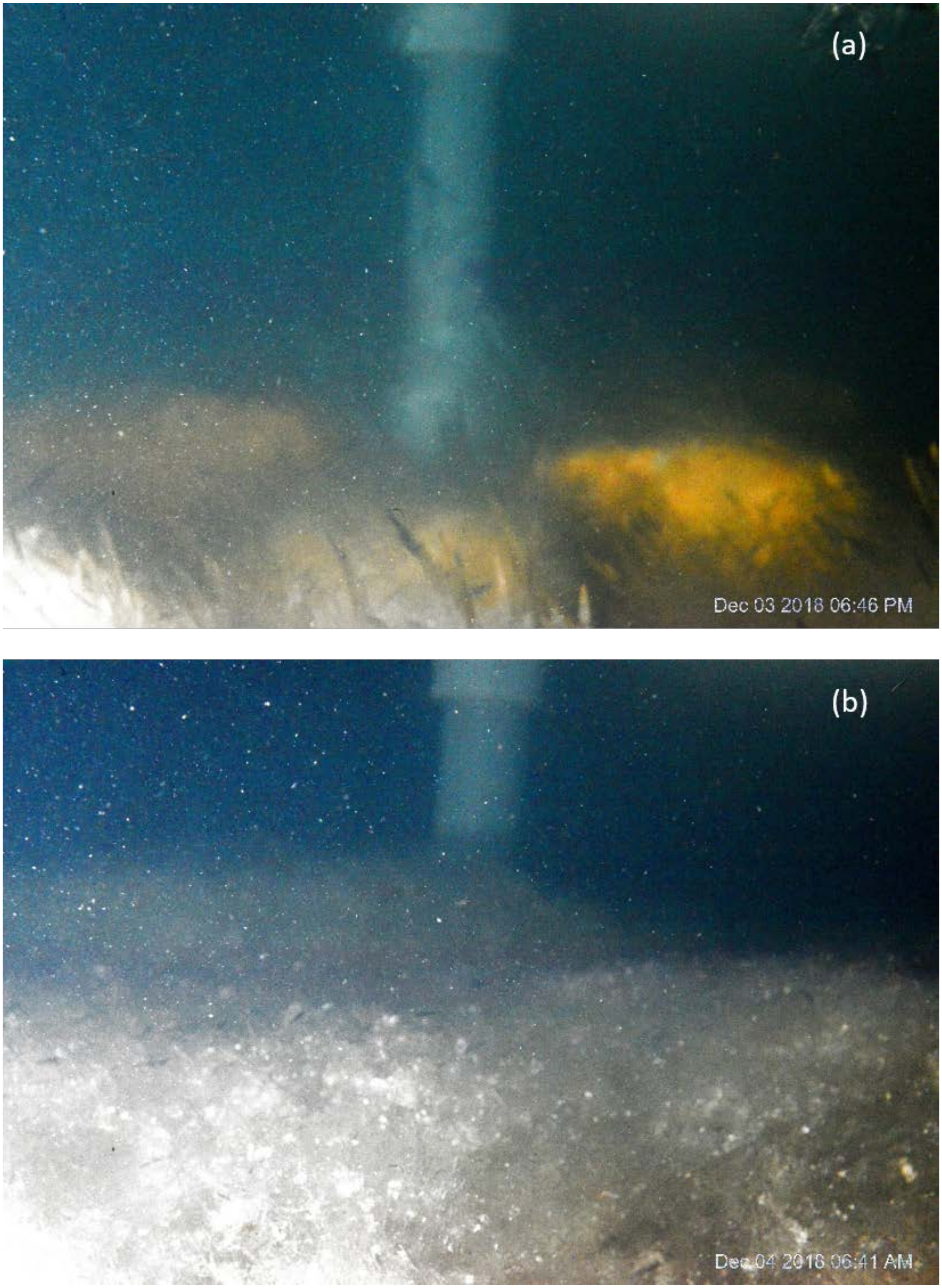

Figure 3: Sample processed images from an anchor ice event on Dec. 3&4, 2018 (Event C) showing: (a) individual crystals growing off the substrate, and (b) anchor ice accumulation over the substrate.

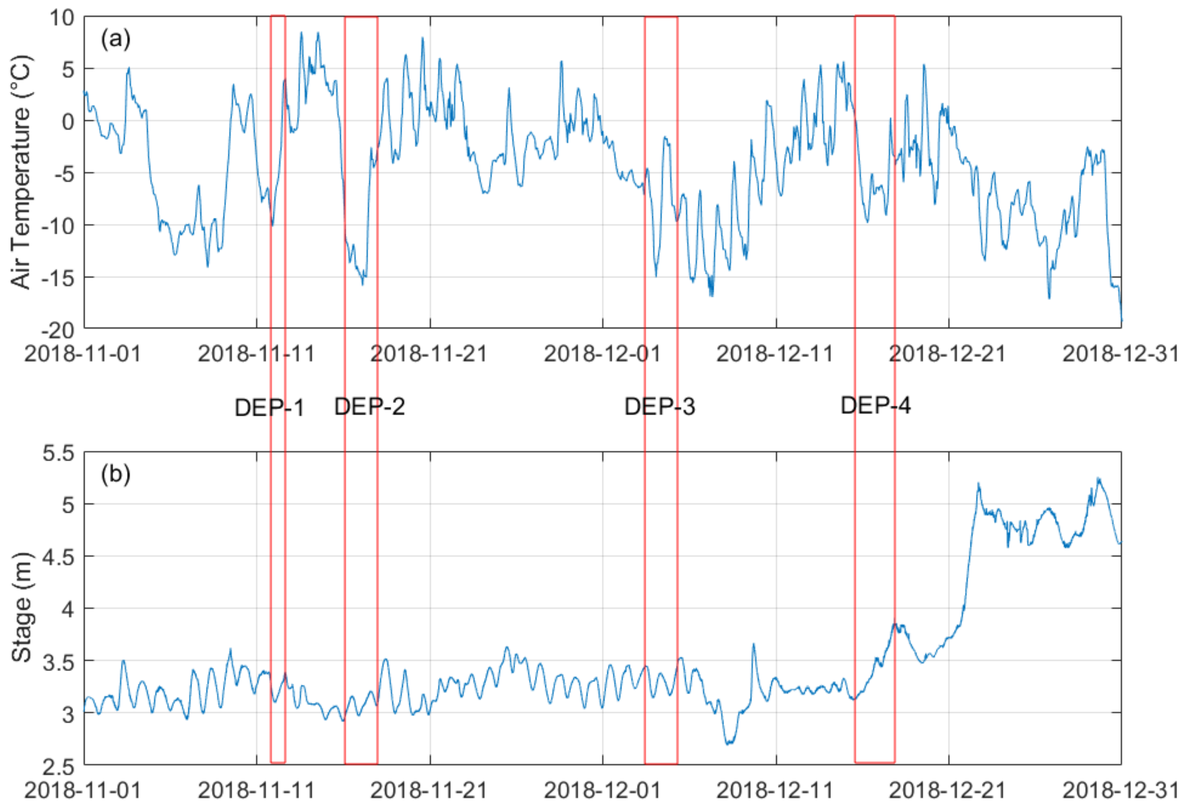

Figure 4: Time series of (a) air temperature and (b) river stage during the 2018 freeze-up season. Field deployments are delineated with red lines.

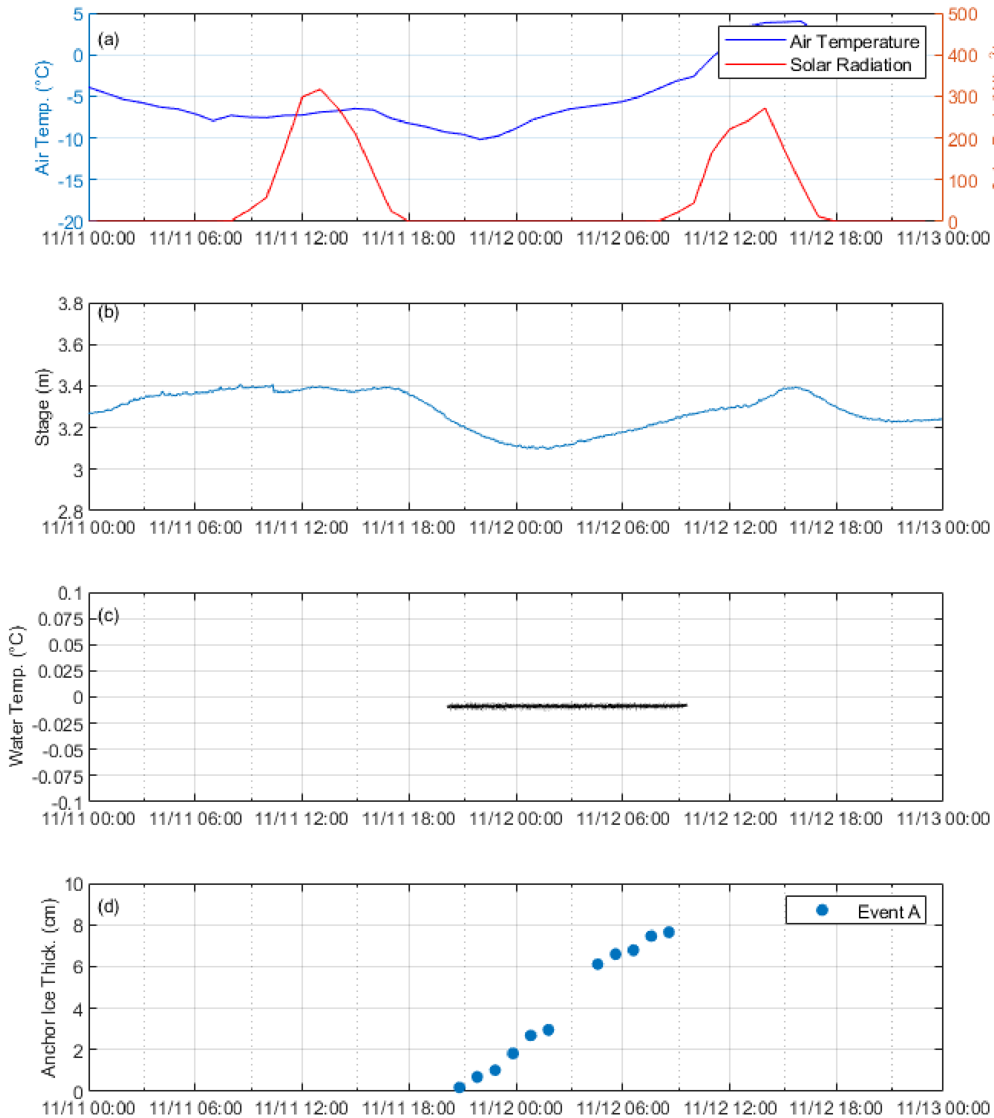

Figure 5: Time series of results during deployment DEP-1 showing: (a) air temperature and incoming solar radiation, (b) water depth at the WSC gauge #05DF001 (c) water temperature on the substrate, and (d) anchor ice thickness above the substrate for Event A.

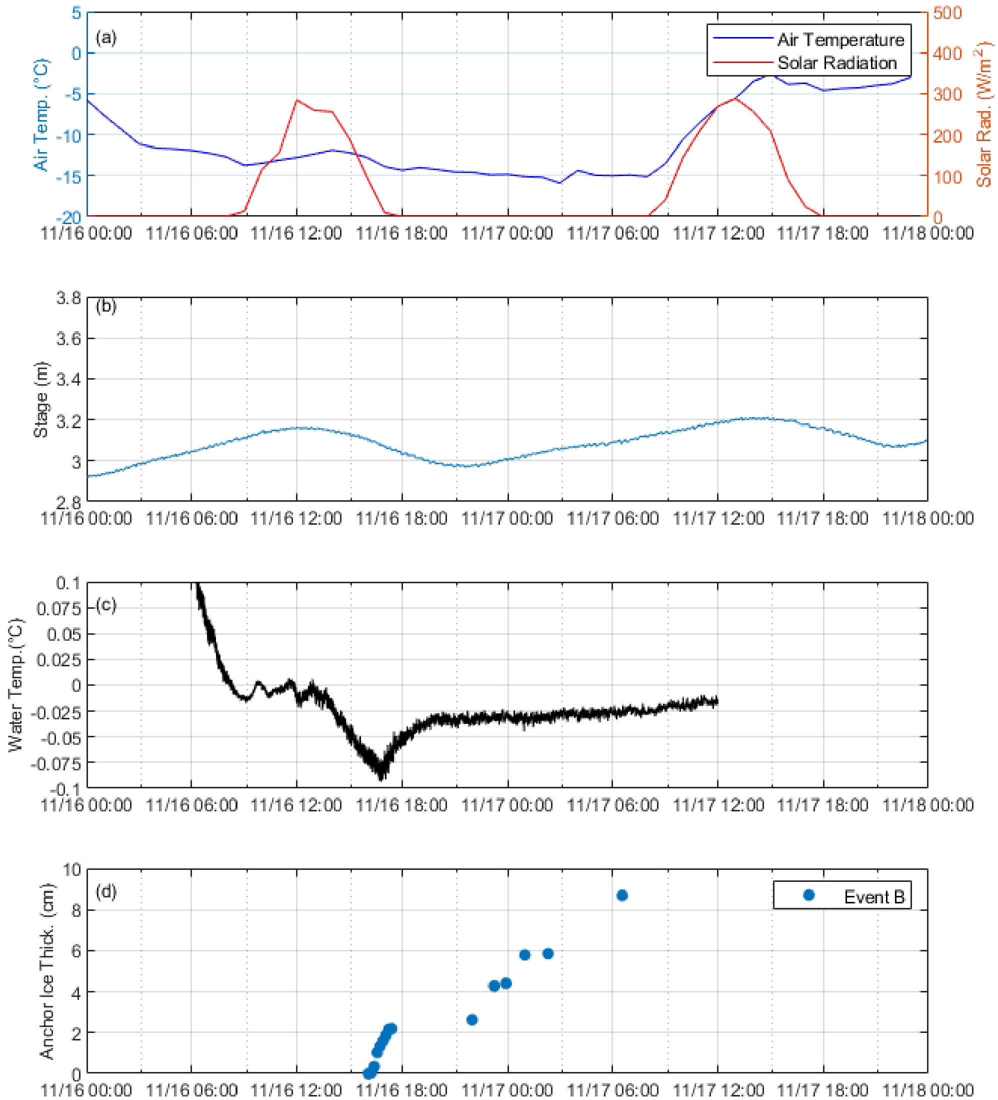

Figure 6: Time series of results of DEP-2 showing: (a) air temperature and incoming solar radiation, (b) water depth at the WSC gauge #05DF001 (c) water temperature on the substrate, and (d) anchor ice thickness above the substrate for Event B.

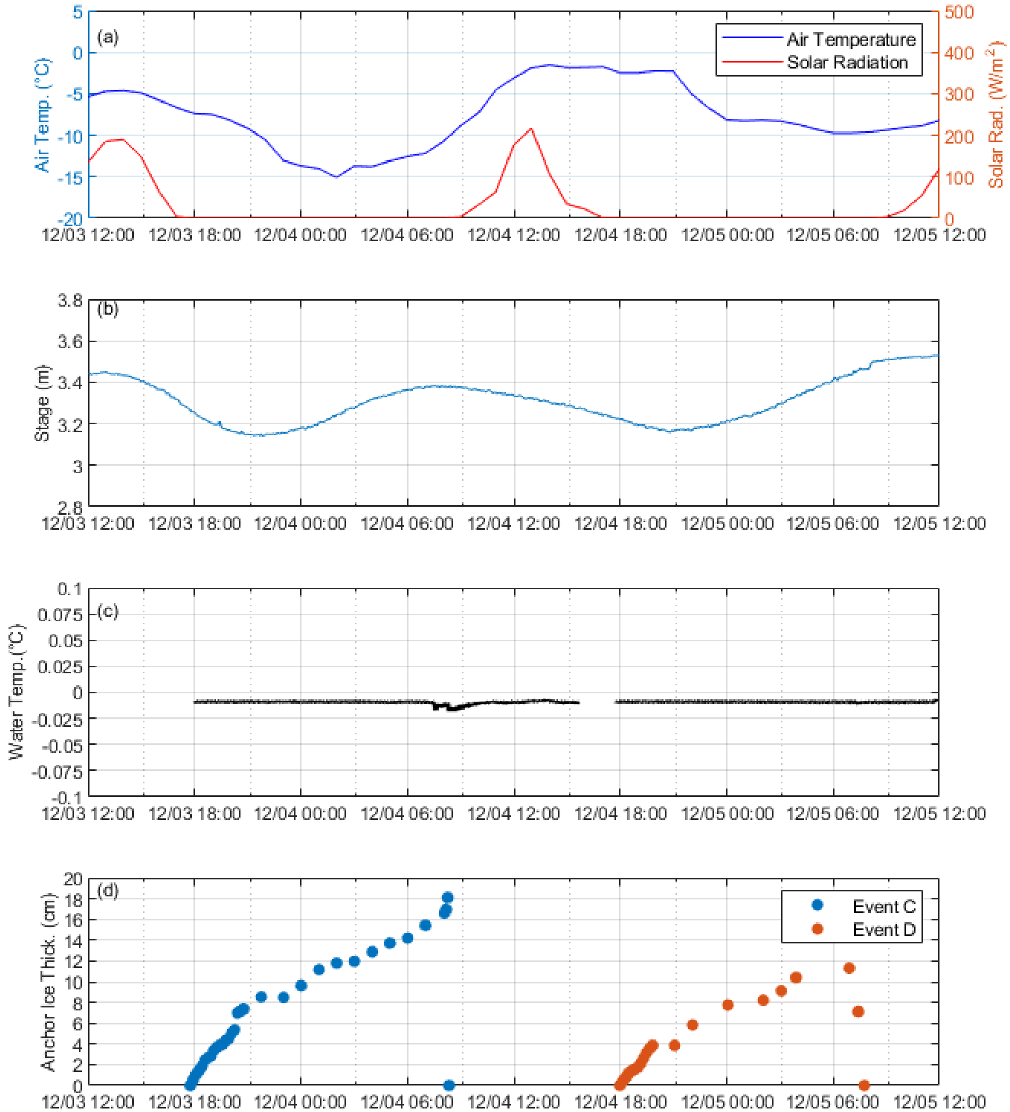

Figure 7: Time series of results of DEP-3 showing: (a) air temperature and incoming solar radiation, (b) water depth at the WSC gauge #05DF001 (c) water temperature on the substrate, and (d) anchor ice thickness above the substrate for Events C and D.

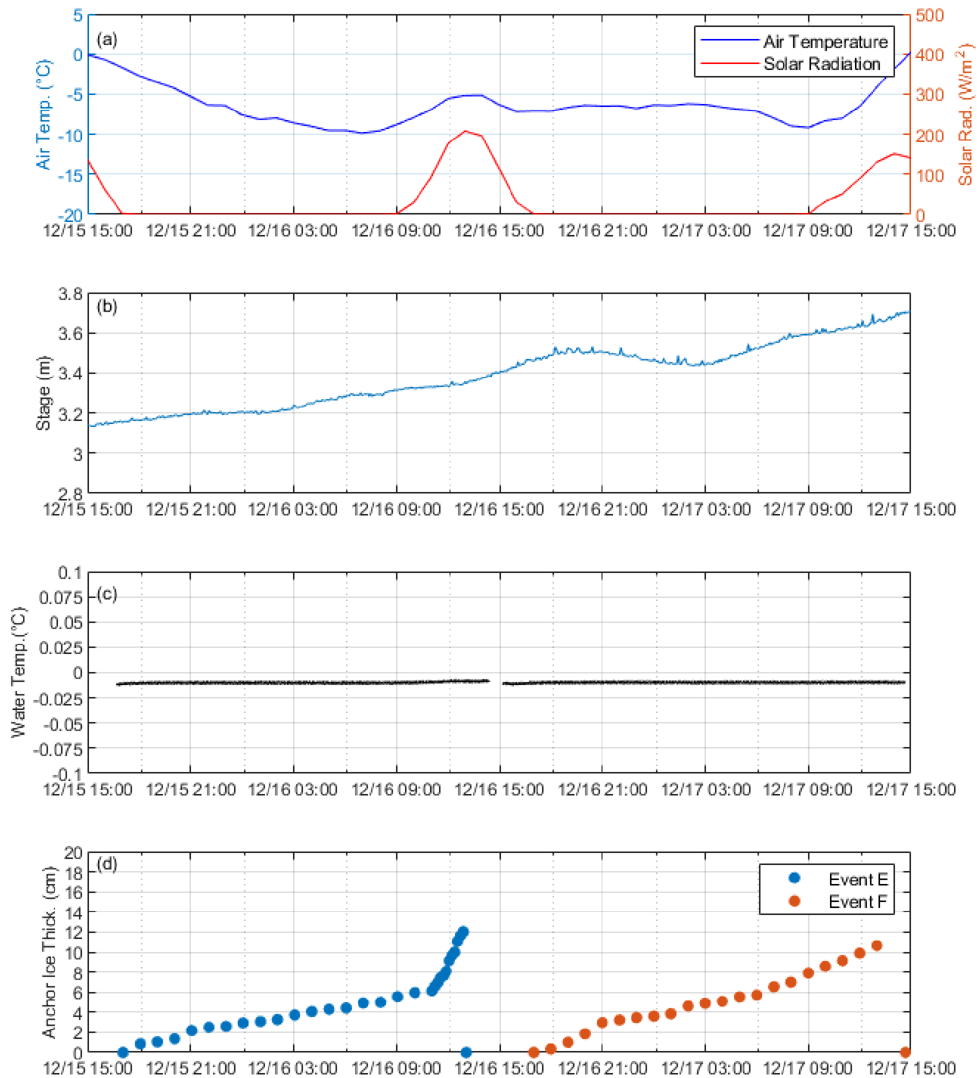

Figure 8: Time series of results of DEP-4 showing: (a) air temperature and incoming solar radiation, (b) water depth at the WSC gauge #05DF001 (c) water temperature on the substrate, and (d) anchor ice thickness above the substrate for Events E and F.

Figure 9: Anchor ice formation on the artificial substrate after the instrument's retrieval on 12-Nov-2018.

Figure 10: Observed anchor ice crystal types (highlighted with red circles) from the 2018 freeze-up season showing (a) curved needle crystals, (b) platelet crystals, and (c) disk crystals.

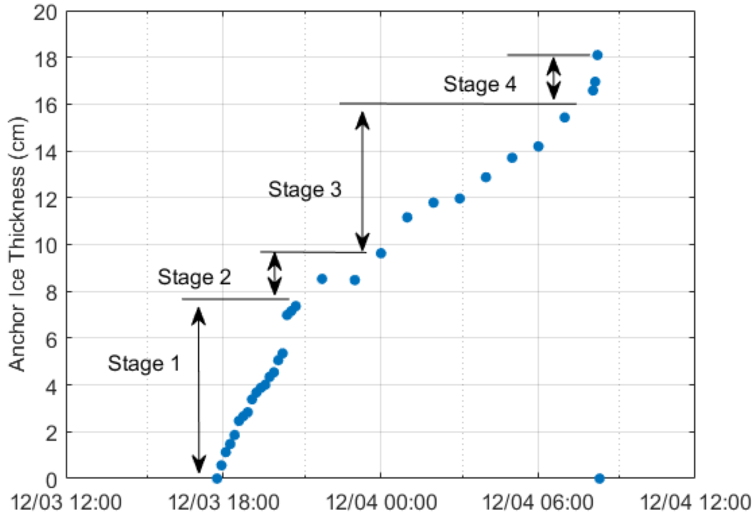

Figure 11: Time series plot of the measured anchor ice thickness during Event C on 3-4 Dec 2018 labelled with the different stages of anchor ice formation, growth and release. Note: Stage 4 shows the "lifting" release mechanism before the total removal of the anchor ice accumulation.

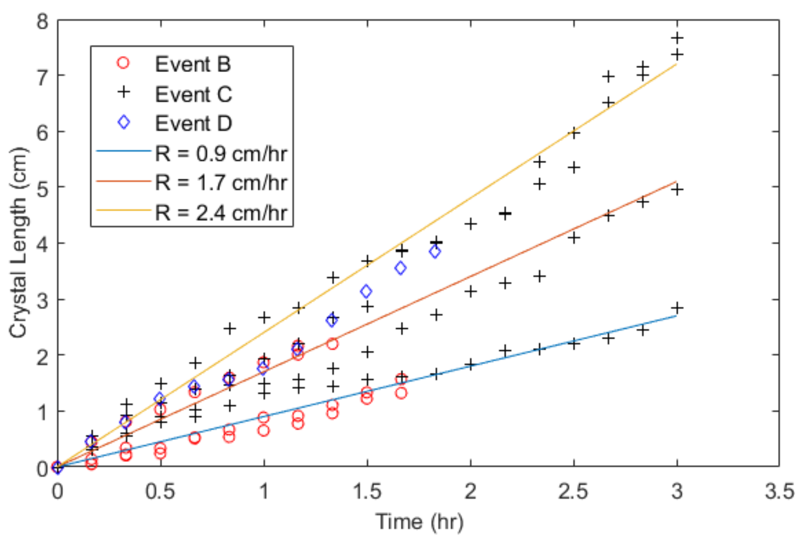

Figure 12: Time series of individual crystal growth (Stage 1) measured from Events B, C, and D. For illustration purposes, linear growth rates, R = 0.9, 1.7, and 2.4 cm/hr were added to the plot.

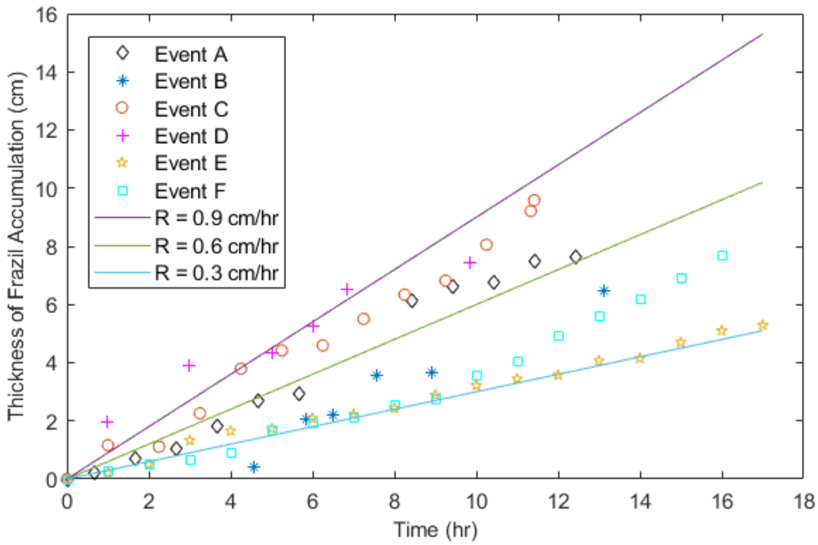

Figure 13: Time series of anchor ice thickness growth due to frazil deposition (Stage 2 and 3) for all the measured events. For illustration purposes, linear growth rates, R = 0.3, 0.6, and 0.9 cm/hr were added to the plot.

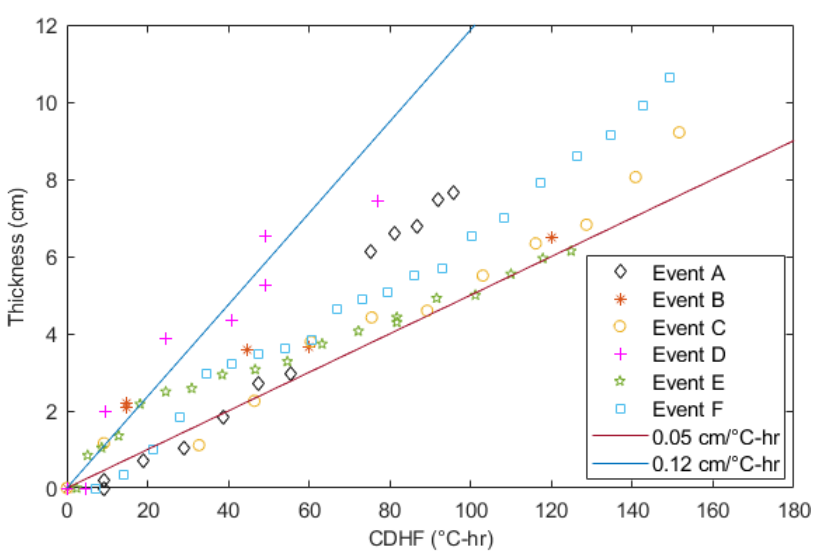

Figure 14: Anchor ice thickness growth due to frazil deposition (Stage 2 and 3) against the cumulative degree hour of freezing, CDHF. The linear rates of 0.05 and 0.12 cm/°C-hr were added to the plot for comparison.