Authors responses to comments posted by Dr. Steve Daly

This article is a valuable contribution to the literature on frazil ice formation in rivers. It is a well-written description of field observations made under difficult conditions using novel instrumentation developed by the authors. The article could very nearly be published as is. However, I do have very few specific comments. I also have some suggestions for the authors. I believe these suggestions would improve the paper, but it is not required that the authors make any of the suggested changes.

> The authors thank Dr. Steve Daly for the time and effort dedicated to providing feedback on the manuscript. We are grateful for the insightful comments that will help to improve the quality of the manuscript. Please find our responses below in blue to the comments/suggestions.

Line 14. The term “relative depth” confusing. Is this the distance from the bottom of the channel or the distance from the water surface?

> The relative depth is the ratio between the height from the river bed to the center of the field-of-view and the entire water depth. We think a clearer term is “fractional height” and will use this in the revised manuscript. This revises the sentence in the abstract to:
>
> “The average floc volumetric concentration ranged from 2.05×10^{-7} to 4.56×10^{-3} and was found to correlate strongly with the fractional height above the river bed.”

Line 22. It is suggested that the authors consider not using the term “sintering.” There is a long history of using the term sintering with regard to ice. The very first uses were applied to the adhesion of ice particles in air when they were held together with some pressure. The reduction in surface energy of the system provides the main driving force for sintering. (Blackford, J. R. J. Phys. D: Appl. Phys. 40 (2007) R355–R385) In the case of frazil ice flocs in supercooled water, however, the frazil discs can simply freeze together due to the heat transfer from the boundaries of the frazil disks to the supercooled water. There is no need to look for a reduction in surface energy of the system to cause the disks to stick together. Also, it is well known that flocs form only in supercooled water. Ice crystals in slush, a mixture of ice and water all at the ice/water equilibrium temperature, do not stick together. Perhaps you are using the word “sintering” in a very general sense to describe solid particles sticking together without regard to the mechanism causing them to stick. That use is imprecise and confusing. The exact mechanism causing the frazil disks to fuse together should be described.

> We agree and will replace “sintering together” with “freezing together” everywhere.

Line 22. It is suggested that the authors consider providing more background on the process of floc formation. The frazil disks are transported by the flow. If the frazil disks are all moving at identical velocities, they cannot collide. Disk collisions require spatially varying disk velocities. Spatially varying disk velocities can result from spatially varying flow velocities and disk varying buoyant rise velocities. There are several mechanisms providing spatially varying flow including turbulent eddies of appropriate size and the influence of the stationary boundary at the channel bottom.

> We agree with this suggestion and plan to revise the description of the floc formation as follows:
>
> "As the particles are transported by the turbulent flow, they may collide with each other due to spatially varying flow velocities created by turbulent eddies, boundary shear and differential rising of particles (Mercier, 1985). Colliding particles may freeze together forming clusters of particles known as frazil flocs in a process called flocculation (Clark and Doering, 2009)."

Line 25. It is suggested that the authors consider the vagueness of the term "grow." In the previous sentence you write: "Frazil flocs grow in size either by the thermal growth of the crystals and/or by further aggregation of individual frazil ice particles or flocs." Then you state "Once frazil flocs grow…" It seems to be that the word "grow" should be applied only to thermal growth of the crystals. Increase in size through aggregation is something different. Perhaps there can be two distinct types of growth, but you should make this clear.

> We agree and replaced "grow in size" with "increase in size" and will revise the manuscript to only use "grow" when describing the thermal growth of crystals.

Line 41 (and other locations). It is suggested that the authors consider not using the terms "residual supercooling" and "principal supercooling" and replacing them with more accurate terms. According to the authors, frazil ice formation has two periods. The first is the "principal supercooling" period and the second, which follows the first, is the "residual supercooling" period. There is a long history of using the term "residual supercooling" going back to the very first experiments of Michel (Michel, Bernard. Properties and processes of river and lake ice. Université Laval, Laboratoire de mécanique des glaces, 1972.). However, the use of the term "residual" is very unsatisfactory. Residual describes what remains after most of something is gone. However, the supercooled temperature of the water is not a residual of the higher levels of supercooled water temperatures that were temporarily present during the earlier principal period of supercooling. The water temperature at all times represents a dynamic balance between the heat loss at the water surface and the latent heat released by the growing frazil ice is suspension and the anchor ice on the channel bed. The water temperature is more-or-less constant during the residual period because the heat loss at the water surface and the latent heat released by the growing ice are equal. In summary, residual supercooling is not left over, it represents a dynamic heat balance exactly as in the principal period. The authors should consider replacing “principal supercooling” with “transient supercooling period” and “residual supercooling” with “steady-state supercooling period.”

This is an interesting suggestion supported by logical arguments. However, as noted the terms principal supercooling and residual supercooling have been in use for more than 50 years and have been used in numerous previous publications. Therefore, we decided to keep using the two conventional widely used terms because we think introducing new terminology will lead to confusion. We will emphasize in the revised manuscript that residual supercooling occurs when a steady water temperature is reached, and that principal supercooling refers to the time period when the water temperature varies transiently.

Line 106. Table 1. It is suggested that the authors consider adding an additional term to their “Summary of the study reach characteristics” table. It is suggested that they add the term e, the turbulent energy dissipation rate per kilogram of fluid. This term strongly influences the heat transfer from suspended particles and the secondary nucleation rate. This can be estimated for both channel flow and laboratory tests. This parameter would allow the reader to compare field sites with previous laboratory tests. The units are generally in Wkg-1 with dimensions of m2s-3.

We have estimated the turbulent dissipation rate from the bed slope and average width and depth listed in Table 1 and will add this data to the table. The dissipation rate was 0.0058 and 0.0051 $m^2 s^{-3}$ in NSR and PR, respectively and was 0.2066 $m^2 s^{-3}$ in the small-steep mountain river KR. We will also revise the discussion section to compare the estimated dissipation rates and the dissipation rates measured in a laboratory tank by McFarlane et al. (2015).

Line 117. Change “capture” to “image.”

Revised as recommended.

Line 265. Change "4.2 Heat flux analysis” to “4.2 Heat flux analysis at the water surface”

Revised as recommended.

Line 265. Heat flux analysis. It is suggested that the authors verify the accuracy of their heat flux analysis at the water surface by modeling the water temperature decline early in the transient period prior to the formation of ice. This could be done for deployments NSR-L.1, NSR-L.3, and NSR-L.4. Two basic and reasonable assumptions would make the model simple and straightforward: that there are no significant gradients of temperature in the longitudinal direction (parallel to the flow velocity) and that the water temperature was well mixed in the vertical direction.

Thank you for your suggestion. We did the suggested calculation for NSR-L3 and NSR-L4. NSR-L1 only captured the warming period of principal supercooling therefore cannot be used. Figure 1 shows an example of calculated and measured water temperature during NSR-L4. The calculated water temperature is consistently lower than the observed. The suggested method assumes no ice is forming and releasing latent heat, and that the water temperature is only affected by the air-water heat flux. However, as shown in Fig. 2 which is a game camera image captured during NSR-L4 near the deployment site, surface ice pans and border ice were observed while no suspended flocs were measured by FrazilCam. Pans, border ice and possibly skim ice may have been growing in the supercooled water and releasing latent heat into the water, thus by neglecting the growth of other ice in the river this method appears to overestimate the magnitude of the water temperature decline. In addition, as noted in the discussion section of the manuscript, the heat flux analysis did not account for the surface ice coverage, which may also contribute to the lower calculated water temperature. We think this calculation will only provide realistic estimates at the very start of river freeze-up when there is no other significant ice formation occurring. Therefore, we concluded the suggested method could not be used to verify the heat flux analysis.

In a previous study the co-authors investigated various formulas used to calculate downwelling longwave radiation and the latent and sensible heat fluxes during freeze-up on the same reach of the North Saskatchewan River. Yang et al. (2023) compared measured and *River1D* modeled water temperatures and determined which combination of formulas provided the most accurate results. This same combination of formulas was used in this study. Therefore, we are reasonably confident that the estimated heat fluxes are sufficiently accurate. We plan to revise the heat flux analysis section to provide a clearer description and justification of the methods used for the heat flux analysis.

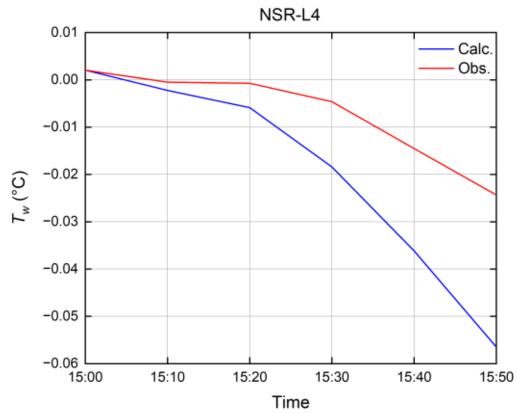

Figure 1. Calculated and observed water temperature time series during NSR-L4.

Figure 2. A game camera image captured 1.5 km upstream of Laurier Park site at 3 pm during NSR-L4.

Line 394. Revise section starting with "Arakawa (1954) discovered …" and ending with "time to grow irregularly." (Line 398) It has long been realized that the stability of the edge of the ice crystals is controlled by the formation of temperature gradients in the water at the ice/water interface when the surrounding water is supercooled (Mullins, W. W. and R.F. Serkerka (1964) Stability of a planar interface during solidification of a dilute binary alloy. Journal of Applied Physics, 35, No. 7, 444-451). The perfect disk shape of frazil ice results from the anisotropic crystalline kinetics combined with the turbulent suppression of temperature gradients surrounding the crystals. Given the ability of turbulence to suppress gradients through mixing, unstable disk growth is typically a special case. Irregular particles generally indicate that the frazil ice particle has been in quiescent regions with exceptionally low turbulence levels. In these regions temperature gradients can form in the water surrounding the ice particle. Small perturbations of the ice crystal boundary encounter colder water because of the temperature gradients and grow more rapidly.

Thank you for providing this very helpful information. We will revise this section as suggested.

Line 385. 6. Discussion. It is suggested that the authors address these two related questions in this section. 1. How do you explain the near constant supercool water temperatures during the steady-state supercooling period based on your observations of suspended frazil disks and flocs? 2. What fraction of the total ice created in the water column is being sampled by the apparatus? The total ice created can be estimated based on the surface heat flux and the water temperature.

1. Constant water temperature during residual supercooling indicates that ice was still being formed and releasing latent heat that balances the heat loss from the surface. This could be due to various reasons. First, in our measurements of frazil flocs, fluctuations and trends in the floc number and volume concentration time series are observed although the mean floc size did not vary significantly during the residual supercooling period. This indicates that there may have been frazil ice particles still growing and forming flocs, releasing latent heat to help balance the surface heat loss. Secondly, as discussed below, suspended flocs comprised only a small fraction of the total ice in the river. During this period anchor ice, border ice, and surface ice pans were likely growing and releasing latent heat that balanced the surface heat loss. We will revise the manuscript and include some discussion of this topic in the section where the residual supercooling time series are presented.

2. We performed the suggested calculations for deployment NSR-L4. Time series of the observed floc volume concentration and calculated ice concentration are compared in Figure 3a. This data shows that the FrazilCam was only sampling up to 2% of the total ice that was forming in the water. It should be noted that this calculation involves significant approximations and assumptions. For example, the net heat flux used in the calculation does not account for the effect of surface ice due to a lack of accurate surface ice data. In addition, mean water depth was used while in reality water depth varied spatially and temporally. This introduce errors in the calculation of the total heat loss from the water surface, and the calculation of the volume of the water being cooled. Therefore, the accuracy of the calculated concentration is quite uncertain but is likely not greater than a factor of two of three. Therefore, we think it would be reasonable to revise the manuscript to say that this analysis indicates that the FrazilCam was only sampling a very small fraction of the total ice being formed, likely 2% or less during these deployments.

We also performed the suggested calculations using data from a recent laboratory frazil ice tank experiment measured by a lab version of the FrazilCam, and the results are shown in Fig. 3b. In the laboratory environment, the water depth is a constant and the surface heat loss can be quantified from the water-cooling rate with reasonable accuracy. The results show that the calculated concentration started rising earlier than the measured suspended floc concentration, which is possibly because the measured data did not include the frazil particles and surface skim ice. The trend in the observed and measured concentrations aligned quite well between 2050 and 2170 s where the calculated and measured time series are overlapping. After that the measured data decreased due to flocs rising to the surface while the calculated time series was still increasing since the calculation does not account for the rising of flocs. Overall, the alignment between the calculated and observed time series prior to the rising of flocs demonstrates that the FrazilCam does provide accurate measurements of the suspended ice concentration. This also suggests that the only time the FrazilCam would be sampling a significant fraction of the total ice being formed in the river would be when suspended frazil is the only ice that is actively growing. This is something that we plan to point out in the revised manuscript.

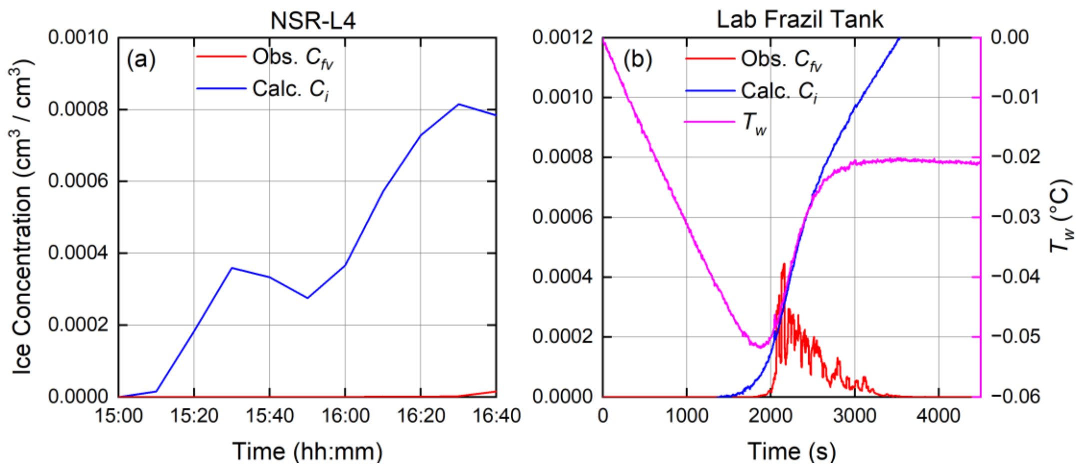

Figure 3. Calculated total ice concentration C_i and observed suspended frazil floc concentration C_{fv} during (a) NSR-L4 and (b) a lab frazil tank experiment using a similar apparatus.

References

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