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Anchor ice cycles: observations from a field study on the Stoke River

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Anchor ice, which is an accumulation of frazil ice on the river bed, is a poorly understood and little studied topic. Past anchor ice studies refer to diurnal anchor ice cycles (i.e., anchor ice forming at night and releasing during daytime) while other type of cycles are not well described. Our study focuses on longer duration anchor ice cycles which were observed in situ. The study was conducted in winter 2013 on the Stoke River near the City of Sherbrooke, QC, Canada. Observations and measurements in the field allowed us to describe a less known type of anchor ice formation/release cycle, hereby named "multi-day cycle". Multi-day cycles are characterized by consecutive days of anchor ice formation. During the day, solar radiation alone was not sufficient to make the anchor ice release from the riverbed. Anchor ice formation stopped when surface ice covered most of the reach. All multi-day cycles monitored on the Stoke River ended with a sudden ice washout caused by important rain or snow runoff events. It appears that multi-day cycles may have significant impacts on river ice processes, such as the formation of ice jams. During these cycles, it was often observed that both surface and former anchor ice layers merged together to form thick blocks of ice. It is suggested that this process may increase the size of ice jams and the frequency of ice jam formation.

1. Introduction

Several studies have been conducted in the last century to better understand anchor ice processes. From Barnes, in 1906, who assessed with his colleagues the “strange mass of ice that grew at the bottom of a river”, to Stickler and Alfredsen, in 2009, who made a more detailed description, our knowledge on this topic has been slowly, but confidently growing with each additional contribution. As more information is available on the topic, it has been increasingly recognized that the presence of anchor may be detrimental in different ways, such as damage to underwater life (Brown, 1999 ; Prowse, 2001; Huusko *et al*., 2007, Turcotte *et al*., 2011), floods, increased sediment transport (Kempema and Ettema, 2010) and even economic losses (Marcotte, 1984; Girling and Groeneveld, 1999). While some studies focused on anchor ice fundamental properties and observations (Barnes, 1906; Altberg, 1936; Osterkamp, 1975; Marcotte, 1984; Parkinson, 1984; Tsang, 1987; Hammar and Shen, 1995; Morse and Richard, 2009; Turcotte and Morse, 2011), others concentrated in subgroups of research topics, which include anchor ice presence/density related to non-dimensional numbers (Froude and/or Reynolds numbers) (Terada *et al*., 1999; Doering *et al*., 2001; Kerr *et al*., 2002; Qu and Doering, 2007; Bisaillon and Bergeron, 2009; Stickler and Alfredsen, 2009), sediment transport (Osterkamp, 1975; Kempema and Ettema, 2010), and numerical modeling (Bisaillon and Bergeron, 2009).

The process of anchor ice formation and release is of particular interest. Diurnal cycles are characterized by anchor ice formation during the night and releasing during day. Multi-day cycles occur when successive days of anchor ice formation are observed with little melt/release. If there are enough consecutive cold days, anchor ice formation is halted by the formation of a surface ice cover. When surface ice covers most of the reach, anchor ice located underneath may release from the riverbed or remain in place. Multi-day cycles end when favorable hydrometeorological conditions (warming usually accompanied by rain) trigger a complete, or near complete, ice washout. The following paper presents research that has been conducted in order to investigate anchor ice formation/release in a steep river basin. More specifically, three cases of a multi-day anchor ice formation/release cycle are presented and discussed.

2. Study site and methods

The Stoke River, located in the province of Quebec, Canada (45° 34’ 06”, -71° 45’ 51”), is a gravel-bed river with an average slope of 1.0% at the study site. The selected reach is 140 m long, it has a bankfull width of approximately 8 m and it flows through a woodland corridor. The mean depth of the river varied between 0.1 and 1.5 m for the studied winter. At the location of the study site, the river drains a watershed of 51 km^2 which covers mostly woodlands (70%) and agriculture lands and/or pasture (30%). The average slope of the watershed is 7%. This particular reach was chosen because many types of river morphological units are present: a narrow riffle, a wide and shallow riffle, straight sections with uniform slope (glides) and deep pools.

A portable meteorological station was deployed to measure incoming solar radiation, air temperature and water temperature. Daily morning trips were made during the fall/winter of 2013 to the site to observe anchor ice formation events. During these visits, data were collected and sketches of anchor ice presence in the studied reach were drawn.

3. Results

Two diurnal cycles and three multi-day cycles were monitored. The two diurnal cycles occurred on November 07 and 16. The multi-day cycles occurred on November 18 - 24 (Cycle MD1), November 25 – December 04 (Cycle MD2) and December 12 - 17 (Cycle MD3).

Figures 1, 2 and 3 show both the air temperature and the daily incoming solar radiation recorded for multi-day cycles MD1, MD2 and MD3 respectively. One can see in Figure 1a) that Cycle MD1 started 5 days after a warm day (November 13) and that the average daily temperature increased during the cycle. Anchor formation occurred on November 18 and 19 (Figure 1b). Solar radiation associated with these days reached 5000 kJ/day (Figure 1a). The minimum water temperature recorded during cycle A was -0.05 °C, which is in agreement with values presented by Altberg (1936) and Arden and Wigle (1972). On November 20, anchor ice formation stopped as air temperature during the night stayed closer to 0°C (Figure 1a) and surface ice covered 50 % of the river width. The cycle ended on November 24 when warm air temperature combined with rainfall heated water long enough to break the bond between anchor ice and the riverbed. Cycle MD2 occurred during colder days (air temperature between 2 °C and -22 °C, Figure 2a). Anchor ice formation occurred between November 25 and 29 during clear (± 4000 kJ/day) and overcast (± 1500 kJ/day) days (Figure 2a). Qualitatively, it was observed that this cycle produced larger anchor ice masses (thickness between 0.2 m and 0.4 m, Figure 2b). Formation stopped on November 30 as air temperature reached - 22°C (Figure 2a), which promoted full coverage of the river reach by surface ice. Cycle MD2 ended on December 03 when a thaw combined with rainfall washed away all river ice. For Cycle MD3, anchor ice formation occurred in two steps: December 12 – 13 and 15 - 17. Warmer air temperatures during the afternoon of December 13 were sufficient to prevent anchor ice formation on December 14 (Figure 3a). It was qualitatively found that smaller quantities of anchor ice formed (thickness < 0.1 m) during the MD3 cycle, which is likely due to warmer mean air temperatures over the period (Figure 3a). A layer of snow covered the studied site on December 17. Snow crystals mixed in the water covered existing anchor ice masses, which thickened them and gave them a lighter color (Figure 3b). Cycle MD3 ended on December 18 due to a thaw combined with rainfall.

During each breakup event, 2-3 ice jams formed in the studied reach. It was observed that these ice jams contained ice blocks consisting of both surface and former anchor ice. Figure 4 shows the edge of a block which is made of 15 cm of surface ice and 10 cm of former anchor ice. It was qualitatively estimated that the largest blocks had a volume up to 2 m^3 (3m x 1.5m x 0.5m) and 1 m^3 blocks were commonly observed. The blocks consisted of 30 – 60 % of released anchor ice.

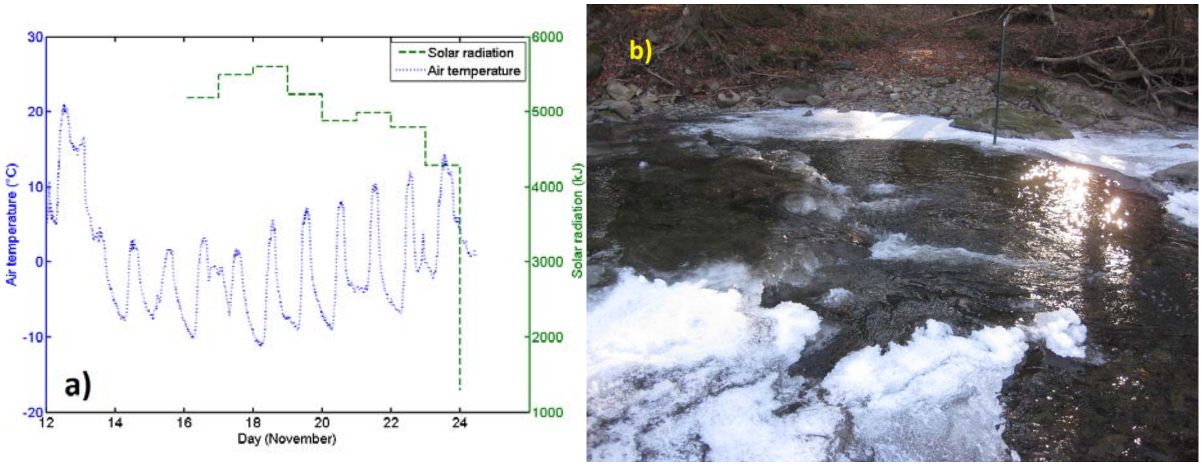

Figure 1 - a) Air temperature and solar radiation for Nov. 12nd to Nov. 24th. b) Anchor and surface ice on Site 3, 20 November 2012.

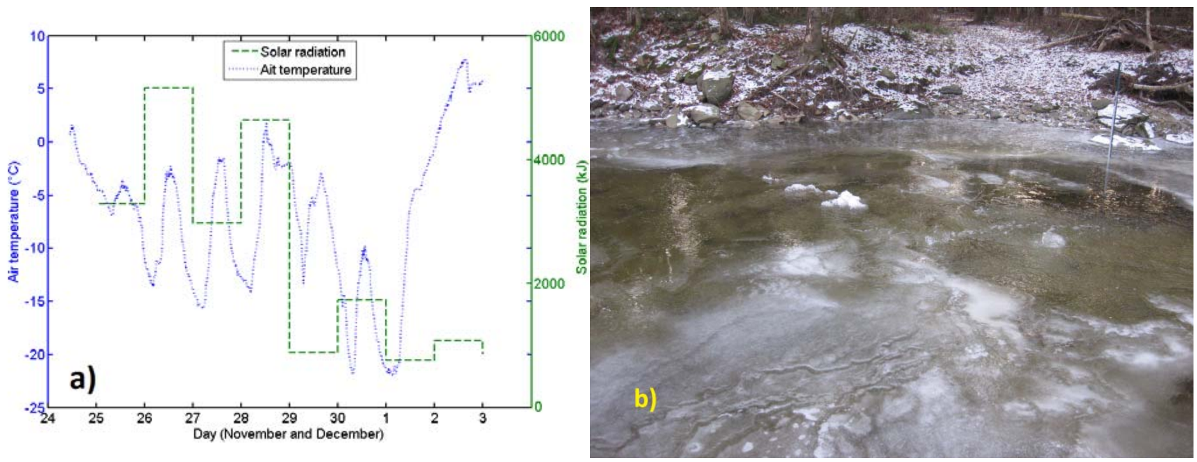

Figure 2 - a) Air temperature and solar radiation for Nov. 24th to Dec. 03th. b) Anchor and surface ice on Site 3, 29 November 2012.

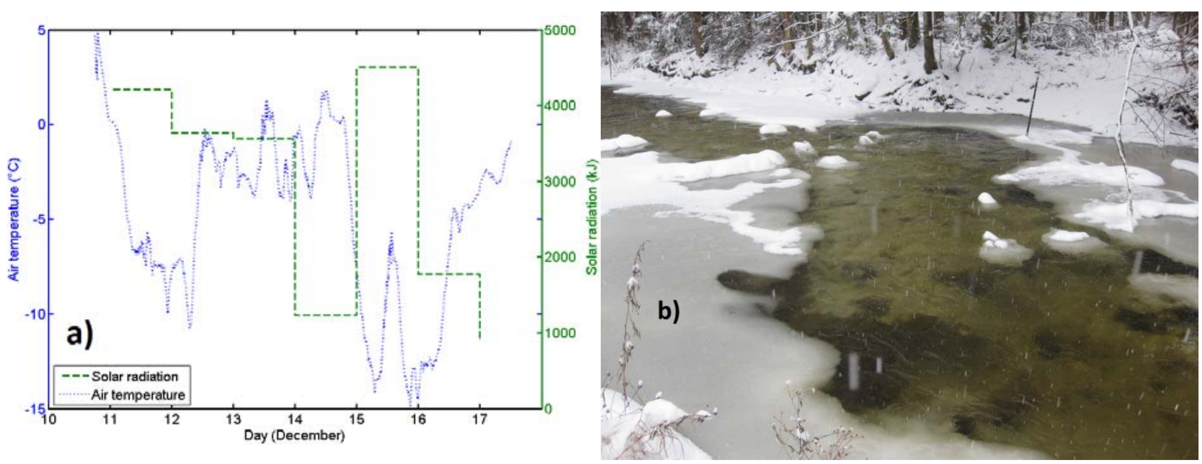

Figure 3 - a) Air temperature and solar radiation for Dec. 11th to Dec. 18th. b) Anchor and surface ice on Site 3, 17 December 2012.

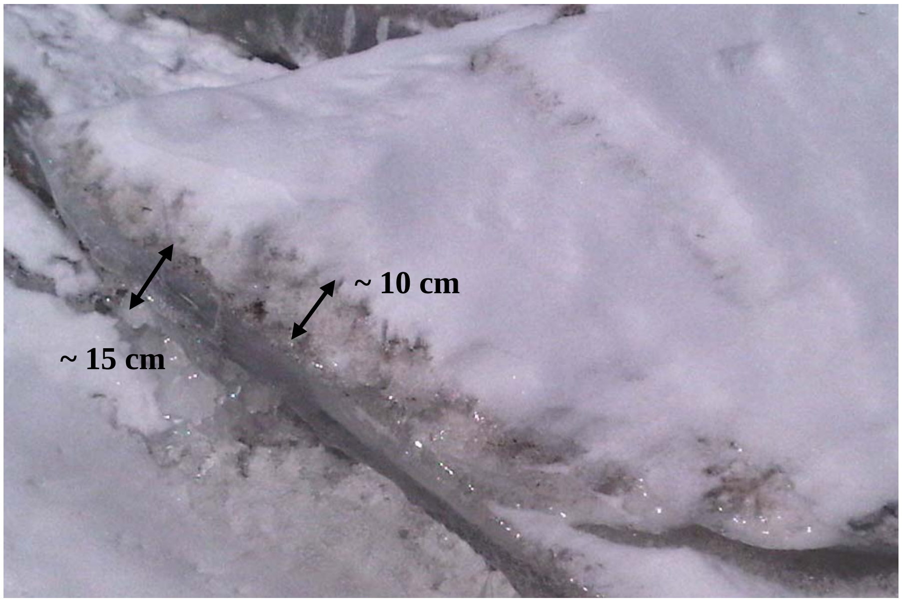

Figure 4 - Block of merged surface ice (15 cm) and former anchor ice (10 cm).

4. Discussion

Some researchers, such as Kempema and Ettema (2010), have only assessed diurnal cycles on their field study, while in the present study multi-day cycles also occurred. The reasons why anchor ice processes follow either diurnal of multi-day patterns are uncertain. It is suggested that differences in the river water heat balance may be one of the reasons responsible of the differences in anchor ice behavior. In that matter, Turcotte and Morse (2011) pointed out that watershed size and slope may have significant effect in the river heat balance. It is suggested that smaller watershed and higher slope may shorten the travelling time of water, which keeps runoff water colder as it receive less solar radiation exposure. The results of the present study support this observation (i.e., multi-day cycles occurring in a river having a small watershed of 51 km² with an average slope of 7% compared with a river showing only diurnal cycles and draining a large watershed of 2000 km², Kempema and Ettema (2010)).

Concerning the phenomenon of ice merging, it is unknown whether anchor ice got released and merged with surface ice, or if the water level dropped and surface ice merged with still-anchored ice, or if frazil ice accumulated under a stable surface ice cover (Allard *et al.*, 2011). Concerning the last case, we believe that it did not happen in our study reach as anchor ice already occupied most of the reach when surface ice formed. Nonetheless, considering that ice thickness can promote ice jam formation (Beltaos 1997; Beltaos and Burrell, 2002), it is suggested that this phenomenon may contribute to the frequency and size of ice jams on the Stoke River because anchor ice merging with surface ice increase ice blocks thickness.

5. Conclusion

In multi-day cycles, anchor ice forms during consecutive days while little or no ice releases from the riverbed occurs. Given enough consecutive days of cold temperature, anchor ice formation is halted when surface ice covers most of the reach. All multi-day cycles monitored on the Stoke River ended when a sudden ice washout was caused by important rain or snow events leading to high river stages. Even though sunny days occurred during multi-day cycles, solar radiation was not enough to prevent further formation and initiate the release of anchor ice masses. During multi-day cycles, it was observed that both surface and former anchor ice layers merged together to form thick blocks of ice. It is suggested that this process may promote the size and frequency of ice jam formation. Further studies on anchor ice should focus on the reasons why multi-day cycles occur in some rivers while only diurnal cycles occur in others.

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