CGU HS Committee on River Ice Processes and the Environment
22nd Workshop on the Hydraulics of Ice-Covered Rivers
Canmore, Alberta, Canada, July 9-12, 2023.

Controls on aufeis formation: lessons from a small Yukon stream

Ashley Dubnick [1], Benoit Turcotte[1], Mederic Girard[1], and Stephanie Saal[1]
[1]*Yukon University Research Centre, 500 University Drive, Whitehorse, YT, Y1A 5K4*
adubnick@yukonu.ca

Aufeis is an ice body that forms by the freezing of successive or sustained overflow events, on ground, engineered structures, or the surface of stream or river ice. Aufeis can have hydrological and hydraulic consequences. Aufeis features store a large portion of the winter flow, leaving dry conditions downstream. They can also block drainage pathways, including culverts and ditches, which can cause local flooding, unsafe driving conditions, and washouts. Previous studies suggest aufeis results from a complex interplay between multiple environmental factors, including snow cover, air temperature variability and water supply, but questions remain about the specific conditions that initiate the formation of ice sequences throughout the winter period and at the onset of snowmelt. This paper documents the thermal, hydrological, and physical aspects of a small stream aufeis on the Dempster Highway, Yukon, throughout winter and identifies overflow sequences that are caused by changes in water supply or local flow conveyance capacity. This work contributes to improving the predictability of overflow and icing events and supports the development of efficient mitigation strategies.

1. Introduction

Aufeis, a German term meaning "ice on top," refers to the development of consecutive ice layers that form ice mounds or ice fields on ground, streams or rivers across cold region landscapes. Aufeis can store large volumes of water throughout the winter period and progressively release that water during and after the snowmelt period. Aufeis therefore contributes to summer baseflow (Kane and Slaughter, 1973; Wanty *et al.*, 2007), providing benefits to communities and ecosystems (Alekseev, 2016; Terry *et al.*, 2020; Huryn *et al.*, 2021). However, aufeis also commonly obstructs spring drainage routes, alters the hydrology of a landscape, erodes stream channels, becomes geohazards and damage infrastructure (Carey, 1973). These ice features often form near infrastructure where the ground's thermal conditions and/or local flow conveyance has been altered (Turcotte *et al.*, 2023b) and can therefore negatively impact roadways and other human-built features during the winter or spring (Turcotte *et al.*, 2023a). Each winter in Canada, the hydraulic capacity of hundreds of ditches and culverts is reduced due to the presence of aufeis, with potential consequences ranging from dangerous driving conditions to complete washouts (Turcotte *et al.*, 2023a). In response, Territorial Governments spend millions of dollars to mitigate and address aufeis-induced damage to infrastructure, often with only partial success.

In North America, aufeis research has been active since the 1960's, mainly following the construction of the Alaska Highway, though the first published observations were available in Europe in the mid-1800 (Wrangel, 1841). Despite several decades of research designed to resolve the mechanisms that cause icing and understand their spatial and temporal distribution, there remains no theoretical framework to reliably and universally predict the location, timing, or intensity of aufeis occurrence. It is widely accepted that aufeis development is most fundamentally controlled by water availability and freezing conditions (Ensom *et al.*, 2020). However, water availability and freezing conditions are, most often, inversely related in cold environments – when freezing conditions are intense and persistent, water availability across a landscape tends to diminish, and vice versa. Under this framework, aufeis development therefore commonly occurs 1) when natural systems are in a form of hydrothermal disequilibrium (water availability and freezing conditions coincide in space and time), or 2) at the interface between two independent systems, such as groundwater and surface environments. For example, aufeis commonly occurs when groundwater drains to the surface during cold winter months. In this case, cold temperatures can even promote drainage to the surface environment because when groundwater freezes *in situ*, it expands volumetrically, and remnant groundwater occupying a confined reservoir is expelled to the surface (Carey, 1973; Ensom *et al.*, 2020). Some case studies have partially resolved local or regional patterns in aufeis development (e.g. Grey and MacKay, 1979; Yoshikawa et al., 1999; Alekseev, 2016) but the full range of conditions that promote icing have yet to be explained, and the phenomenon remains difficult to anticipate, even to those with a significant winter highway maintenance experience.

Here, we present field data from the first season of a multi-year study that aims to document the thermal, hydrological, and physical characteristics of many recurring aufeis sites on the Dempster Highway, Yukon. We identified five discrete "active icing" (overflow and freezing) events near a small creek during the 2022-2023 winter period and discuss the environmental conditions that may have contributed to the aufeis development. This project aims to improve the predictability of overflow and icing events along northern transportation corridors, where aufeis presents a seasonally persistent geohazard, to help identify the most effective and efficient forms of mitigation.

2. Methods

2.1 Field site

The primary study site is located at Km 32.6 of the Dempster Highway, just north of the Klondike Highway near Dawson City, Yukon. The stream drains a watershed that is characterized by sub-arctic tundra and boreal forest that covers an elevation range from 700 m to 1330 m (Figure 1). The area is almost entirely underlain by permafrost (Heginbottom *et al.*, 1995) with considerable groundwater flow, which affects perennially frozen ground and facilitates regional icing (Stockton *et al.*, 2019). Five culverts (ranging from 0.4 m to 2.3 m in diameter) drain this watershed across the highway at the aufeis site (the lower three are shown in Figure 1c). The hydraulic structure redundancy at this location represents a maintenance response to the frequency of ice blockage over the winter period. The aufeis that develops in this area commonly extends over 200 m parallel to the highway and 30 m perpendicular to the highway and reaches the top of the snowbank elevation (>3.8 m thick). Maintenance is often required at this site, including excavation of aufeis and heating of culverts to restore partial evacuation capacity (Turcotte *et al.*, 2023a).

Other supplementary study sites were established along the Dempster Highway at locations identified by the Department of Highways and Public Works (Yukon Government) as aufeis-affected areas (Figure 1a). These sites include km 33.8 at a small stream crossing (Figure 1f) f), km 86.0 at a mid-size stream crossing on the East Blackstone River (Figure 1g), and km 143.5 where the road parallels the Blackstone River (Figure 1h). These sites were monitored to provide regional context on the timing of aufeis development under different hydrological settings.

2.2 Thermistor chain

We used a High-resolution Snow and Ice Mass-Balance Array (SIMBA; Jackson et al., 2013) to monitor the temperature and thermal characteristics of the aufeis throughout winter. The SIMBA unit involves a 3 m chain of temperature sensors (each with an accuracy of 0.065 °C), spaced at 2 cm intervals, connected to a logger box. The unit was installed October 28, 2022, on a wooden structure so that the thermistor chain was suspended vertically, approximately 10 m away from the main stream channel and 1 m away from an overflow channel (Figure 1c, d, e). The bottom 25 sensors on the thermistor chain were installed vertically in the substrate to measure the temperature of the ground from the ground surface to 50 cm depth, leaving 125 sensors (250 cm) above the ground, with the uppermost sensor consistently measuring air temperature (T_{air}). The unit was programmed to collect temperature measurements at each sensor every 6 hours until April 28, 2023.

The SIMBA is also capable of collecting heat profiles, whereby the sensors are gently heated and temperature profiles are collected during the heating and subsequent cooling periods. The change in temperature during the heating and cooling periods at each sensor reflect the heat capacity of the surrounding material and can therefore be used to distinguish air, ice, snow and water. The SIMBA unit was programmed to conduct a 120 second heating cycle every 24 hours, with temperature measurements collected at the end of the heating period (T_{120}). Ice/water was defined as having T_{120} of < 1.55 °C while air was defined as having $T_{120} \geq 1.55$ °C. These data were used to define the ice surface. The snow surface was delineated manually by defining the maximum elevation at which temperature fluctuations were muted compared to the temperature fluctuations that occurred in the overlying air. Snow depths were verified 3 times with field measurements throughout the season.

2.3 Water level logger

A Solinst Levelogger 5 was installed in the main channel, on a custom anchoring system (Turcotte *et al.*, 2017). The sensor was programmed to collect pressure and temperature measurements every 30 min. Pressure was converted to water level by subtracting the barometric pressure at a nearby weather station.

2.4 Ice core

An ice core representing the top 0.7 m of the aufeis was collected within 5 m of the SIMBA unit on April 1, 2023, using a Kovacs MarkII coring system. The ice core was bagged and transported frozen to the laboratory at Yukon University and the remnant hole was filled with snow to minimize thermal and hydraulic impacts to the aufeis for the remainder of the monitoring period. In the laboratory, a 1 cm thick section was cut along the length of the core and was photographed with polarize back light and a polarized camera lens once the section had melted to ~1 mm thick.

2.5 Time-lapse cameras

Time-lapse cameras were installed on nearby trees, with frames aligned perpendicular (Boly SG2060-K) and parallel (Reconyx Hyperfire 2) to the highway and set to collect images every day between 12:00 and 16:00. Additional time-lapse cameras were also installed to monitor icing at supplemental study sites at kms 33.8, 86.0 and 143.5 along the Dempster Highway (Figure 1).

3. Results

3.1 2022-2023 Climatological context

Weather conditions preceding winter were characterized by extremely wet conditions, with record-high October flow in nearby rivers (27- and 57-year records at Water Survey of Canada stations 10MA003 and 09EA003, respectively). It is therefore assumed that regional groundwater levels were relatively high prior to winter. The 2022-2023 winter was milder than usual in the region, with 2900 degree-days of freezing compared to an average of 3300 degree-days of freezing at Dawson City, located ~40 km to the southwest. The winter was also characterized by an anomalously high early season snowfall and a spring (April 1st) snowpack that was 130 % of historical median snow water equivalent (Water Resource Branch, 2023)

3.2 2022-2023 Icing events

The formation of aufeis at the study site occurred between November 2022 and April 2023, reaching a maximum thickness of 1.4 m, with a maximum overlying snow depth of 30 cm (Figure 2). The formation of this aufeis occurred during five primary icing events (Figure 2, Figure 3), as described below:

<u>Event A (Nov 11-15, 2022)</u>

Icing Event A lasted only 3 days and resulted in 0.08 m of vertical icing (Figure 2). This event occurred before the first snowfall that persisted across the landscape. Leading up to this event, T_{air}

was consistently < 0°C for ~2 months, reaching -30°C for the first time of the season the week prior to Nov 11 (Figure 3b), which froze the ground to a depth of >50 cm (Figure 2b). Icing began once temperatures rose to > -10°C (Figure 3b) and water pressure rose by ~0.40 m in the underlying stream (Figure 3e). Icing remained active until snowfall occurred (Figure 3d) and water pressure subsided to baseline (Figure 3e). This icing event was followed by warm (-5 °C) T_{air} (Figure 3b).

<u>Event B (Nov 17 – Dec 1, 2022)</u>

Event B lasted 15 days (11 of which involved active icing) and resulted in an additional 54 cm of vertical aufeis (Figure 2). This event started when T_{air} dropped below -20 °C and continued while T_{air} rose to -5°C then subsequently fell again to -30°C (Figure 3b). Icing stopped when a snowfall event occurred (Figure 3d) and T_{air} remained relatively warm (~-10 °C) (Figure 3b). Interestingly, water pressure in the nearby stream remained low throughout this event (Figure 3e), as if there was a hydraulic disconnection between the overflow sources and the underlying stream.

<u>Event C (Dec 12 - 21, 2022)</u>

Event C lasted 14 days (of which only 6 involved active icing) and resulted in 14 cm of vertical icing (Figure 2). This event started when T_{air} was relatively cold (-30°C) and snowfall occurred (Figure 3d). Icing stopped once the aufeis reached the snow surface (Figure 2) and T_{air} dropped to <-40 °C (Figure 3b). Water pressure in the stream also remained near base level during the event, gradually receding by 0.05 m before icing stopped (Figure 3e). The aufeis surface remained dry after this event while T_{air} was cold (<-20°C) (Figure 3b) comprising the end of the most intense cold spell of the 2022-2023 winter. The water pressure in the stream started to rise after Event C, until the onset of Event D (Figure 3e).

<u>Event D (Dec 27, 2022 – Jan 3, 2023)</u>

Icing during Event D was intermittent, with 6 days of new overflow/icing, resulting in 18 cm of vertical aufeis development over a period of 11 days (Figure 2). Aufeis thickening was documented at other study sites (km 33.8 and km 86.0) during the same period. This event started when T_{air} began to warm (from -15°C to 0°C) following the cold spell of Event C (Figure 3b) and persisted during an absence of snow (Figure 3d), forming relatively dense ice with large crystals (Figure 4a). Icing stopped once the stream water pressure declined (Figure 3e) and snowfall occurred (Figure 3d). Icing remained stalled for ~2 months following this event, through moderate (~-20°C) and stable T_{air} (Figure 3b), and an increasingly thick snow cover (Figure 3d) that functioned to keep ice and ground temperatures warm (>-2°C) and stable across the vertical profile (Figure 2).

<u>Event E (March 2 – 20, 2023)</u>

Icing Event E lasted 5 days, resulted in an additional 34 cm of icing (Figure 2), and coincided with icing events at other study sites (km 33.8, 86.0 and 143.5). The icing started under a snowpack that was almost 30 cm thick (Figure 3d), once diurnal fluctuations in T_{air} consistently exceeded 10°C (Figure 3c). The ice formed during this event had a granular structure with small crystals (Figure 4b). Throughout the icing event, water pressure in the underlying stream remained near base level (Figure 3e). The underlying stream was accessed in mid-February during conditions of similar water pressure by augering through the aufeis, and observations at this time suggest the water was flowing freely in an air-filled gallery. Aufeis development ended when overflow reached the snow surface (Figure 2), new snowfall occurred (Figure 3d), and daily mean T_{air} exceeded 0°C (Figure 3b).

At the end of the 2022-2023 winter, the main (2.4 m-diameter) culvert was only partially blocked by the aufeis. Water was still flowing under the ice and there was an air gap between the aufeis surface and the culvert ceiling. Icing commonly completely blocks the culverts at Km 32.6 as well as at many other stream crossings along the Dempster Highway (Turcotte et al., 2023a).

4. Discussion

A number of studies have examined the regional and broad-scale extent of aufeis (e.g. Brasseur et al.; Li et al., 1997; Morse and Wolfe, 2015; Makarieva et al., 2019), and found icing dynamics and aufeis distribution are site- (and/or region-) specific, depending on local factors such as geology, permafrost, groundwater, air temperature and snow cover. We found the aufeis at our main study site to be thinner and less extensive at the end of the 2022-2023 winter, than at the end of the 2021-2022 and 2020-21 winters, when it reached the road surface and interventions were required to restore the drainage capacity of some culverts. The 2022-2023 winter was characterized by higher preceding baseflow conditions, deeper winter snowpack, and warmer air temperatures than the prior two seasons. Though high baseflow is often associated with intense icing activity by increasing water supply, the deeper snowpack and warmer air temperatures both represent environmental controls that have impeded aufeis formation at other sites (Carey, 1973; Yoshikawa *et al.*, 2007; Alekseev, 2016).

4.1 Processes that promote aufeis formation

Most icing events at this study site occurred in the initial two months of winter (Nov and Dec), with no icing throughout most of January and all of February, and only 30 cm of icing in March. Ambient T_{air} has been previously correlated with aufeis extent (e.g. Morse and Wolfe, 2015), but T_{air} fluctuations potentially control the magnitude and duration of discrete icing events. Events A and D were preceded by cold T_{air} and low stream water pressure, and were followed by overflow and icing that coincided with warming T_{air} and a rise in stream water pressure (Figure 3b, Table 1). These events may be associated with overflow sourced from the main stream (Table 1). During intense cold periods, ice formation occurs upstream and commonly results in depressed flow downstream. As T_{air} rises, upstream water storage ends and streams experience a rise in flow (Turcotte and Nafziger, 2021). This rise can overwhelm the under-ice conveyance capacity of the conduits and can result in pressurized water and condition conducive to overflow.

In contrast to Events A and D, overflow events B, C and E occurred during very different conditions, suggesting a distinct overflow mechanism (Table 1). Events B, C and E coincided with cooling T_{air} in the days/weeks prior (Figure 3b) and a new or persistent snow cover (Figure 3d). The stable and low water pressure in the underlying stream (Figure 3e) suggests it unlikely supplied the overflow during these events, since flow probably remained within the conveyance capacity of the air gallery. Instead, frost penetration into a confined water-bearing layer, talik or active layer in the ground may have increased groundwater pressure and initiate diffuse overflow at the surface environment (Table 1), as documented by (Carey, 1973). The water may have emerged close to the study site or may have drained towards this location beneath the insulating snow covers. Overflow during Event E could have also been alternatively or additionally supplied by local snow melt resulting from intensifying solar radiation and relatively high daytime T_{air}, which commonly promotes aufeis development in spring (Kane, 1981; Yoshikawa *et al.*, 1999, 2007). Previous studies suggest that snow can melt at T_{air} as low as -10°C, with favourable levels of solar and atmospheric radiation, humidity, surface roughness and albedo (Kuhn, 1987).

4.2 Processes that halt aufeis formation

Overflow events at the study sites did not persist for long periods. Icing affiliated with Events A, D and E stopped at the onset of warm T_{air} (>0 °C). Though these warm conditions may have increased water supply from snowmelt, especially in combination with intense solar radiation in March (Event E), overflow and icing did not persist. The additional heat may have instead promoted the thermal expansion of the drainage system, resulting in increased drainage capacity that accommodated the streamflow without overpressure. The absence of icing following Event E, when snowmelt rates would have increased, is particularly notable since icing commonly occurs during periods of spring snowmelt (Kane, 1981; Yoshikawa *et al.*, 1999, 2007). However, meltwater produced slowly (under moderate spring T_{air}, Figure 3b) is less likely to overwhelm the drainage system as the network of surface and under-ice channels expands. For Events A and D, it is also possible that the upstream water storage release event associated with the preceding cold spell ended (Table 1), returning the stream to baseflow conditions.

Snow is an effective insulator so under the presence of a relatively insulative snowpack, (i.e., immediately following a substantial snowfall), ground heat can maintain subsurface and under-ice flow paths, limiting groundwater seepage and overflow. The presence of snow would also increase the insulation at hydraulic restrictions along the flow paths, including the extremities of downstream culverts. At local scales, the absence of a thick early winter snow cover is known to facilitate aufeis development while thick early winter snow cover is known to inhibit aufeis development (Grey and MacKay, 1979; Yoshikawa *et al.*, 1999; Alekseev, 2016). The absence of overflow in January and February can be explained by the presence of a thick snowpack during this period (Figure 3d). The area experienced a record precipitation anomaly in January 2023 (Water Resource Branch, 2023). This period was additionally characterized by moderate and stable T_{air} which would have also contributed to stabilizing upstream water supply and preserving the local under ice (and underground) flow conveyance.

Though snowfall may have inhibited icing at multiple instances during the 2022-2023 winter, its role in aufeis formation at this location was complex. Snow is a porous medium that is known to distribute water vertically via capillary rise (Cécile Coléou *et al.*, 1999), a process that has been observed previously in wind drifts on aufeis (Turcotte et al., 2023b). In the case of multiple icing events documented in this study (Events B, C, and E; Figure 2), snow appears to have promoted the vertical migration of water, freezing amongst the snow and yielding granular ice that maintained some structural characteristics of the proceeding snowpack (Figure 4). In the case of Events C and E, icing stopped once it reached the snowpack surface (Figure 2; Table 1). It is possible that icing continued after these events, but occurred horizontally rather than vertically so was therefore not detected by our instruments. In summary, snow plays a complex and dynamic role in both promoting and inhibiting aufeis development.

5. Conclusion

This research documents the first of a multi-year study designed to monitor icing events at different sites on the Dempster Highway, Yukon, in which aufeis consistently develop. We used a novel approach (SIMBA temperature sensor array) to document the formation of an aufeis and its thermal characteristics at high vertical and temporal resolution, in addition to timelapse cameras and a water level sensor in the underlying stream. In winter of 2022-2023, we found icing to occur over five discrete periods, separated by periods of stable conditions in which water supply was limited. Two of these events (A and D) appear to have been driven by an increase in water supply, following a flow depression in the underlying stream that likely resulted from upstream icing and/or water storage events during a preceding cold period. The other three events (B, C and E) appear to have been driven by frost penetration into groundwater unit(s), which initiated diffuse overflow at new locations in the surface environment. Event E could have also been caused by local snowmelt. We found snowfall to play an important but complex role in the formation of aufeis, by both promoting and suppressing overflow and icing events. These results suggest that multiple, complex processes control aufeis formation at a single site over a single winter. Moreover, these processes involve cascading effects from upstream to downstream.

Further research is required, particularly at broad spatial scales and at sites upstream or upslope of aufeis, to fully document the seasonal dynamics of groundwater seepage, upstream water storage, and snowfall and their impacts on overflow and icing. A parallel effort is also underway to develop and test aufeis mitigation measures at stream crossings. Documenting the success of mitigation measures at sites with known processes of aufeis formation will produce a robust framework for understanding, managing and mitigating aufeis across cold regions.

Tables

Table 1: Summary of observations and the processes that may have controlled the start and end of the five icing events

	Icing starts			Icing ends		
	Observation		Interpretation	Observation		Interpretation
	Air Temp	Stream pressure		Air Temp	Snow	
A	↗	↗	- Stream water source	↗	*	- Sufficient heat to increase flow conveyance - End of storage release event
B	↘	—	- Groundwater source	↘	*	- Upslope freezing - Snow insulation stalls downward migration of the freezing front and groundwater release
C	↘	—	- Groundwater source	↘	— ↑	- Icing switches from predominantly vertical to predominantly horizonal - Upslope freezing
D	↗	↗	- Stream water source	↗	*	- Sufficient heat to increase flow conveyance - End of storage release event
E	↕	—	- Groundwater source - Local snow melt source	↗	* — ↑	- Icing switches from predominantly vertical to predominantly horizonal - Sufficient heat to increase flow conveyance

↗ Increasing/high ↘ Decreasing/low ↕ High & low/ fluctuating — Stable ↑ Icing stops at snow surface * Snowfall

Figures

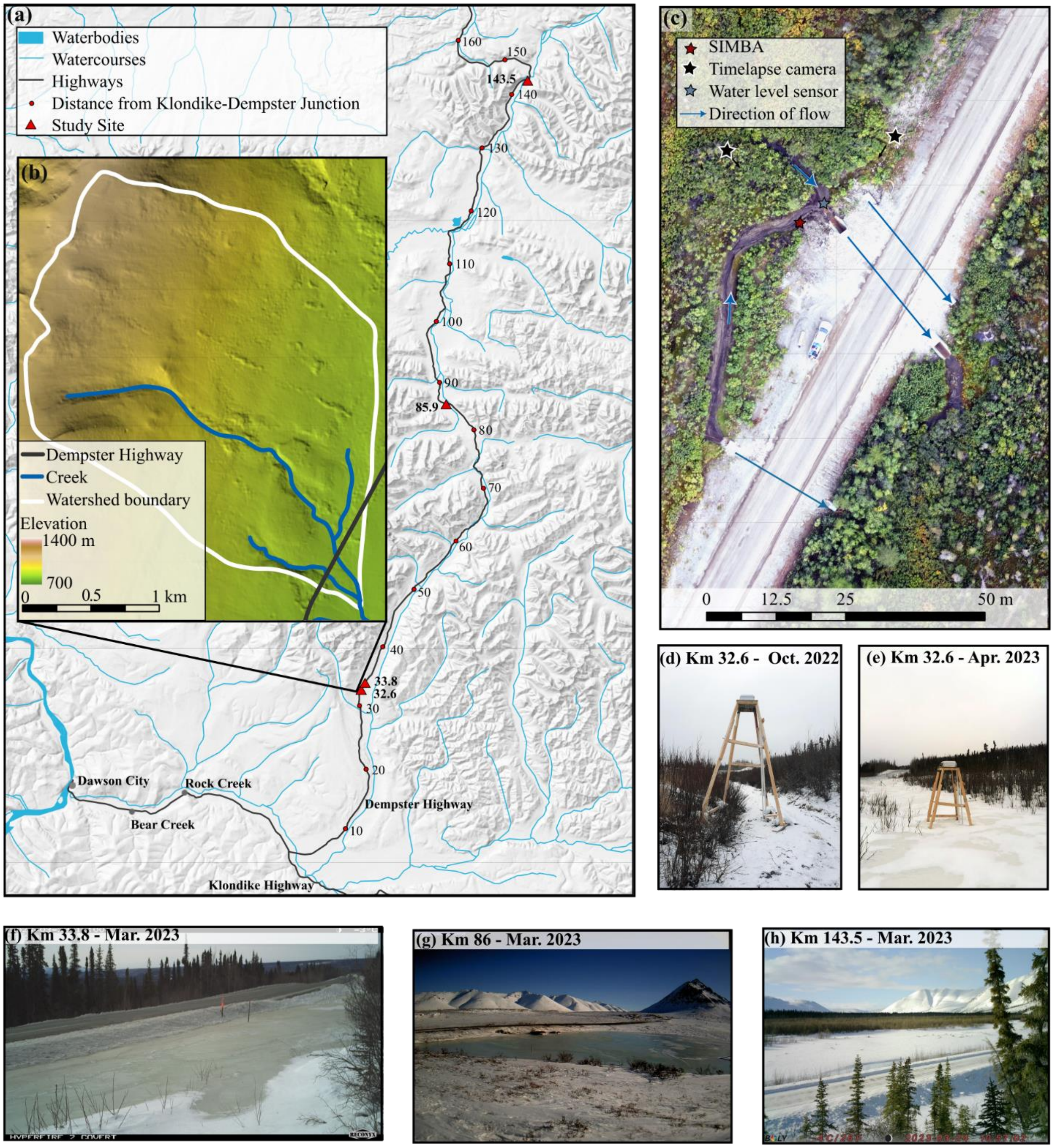

Figure 1. (a) Study sites along the Dempster Highway, Yukon including (b) the watershed and topography and (c) drone imagery collected Fall 2022 at the primary study site, showing locations of instrumentation. SIMBA instrument (d) after installation in late October, 2022 and (e) on April 2, 2023 after ~1.5m of aufeis. Photos from timelapse cameras at secondary study sites, including (f) km 33.8, (g) km 86 and (h) the Tth'oh Zraii Njik/Blackstone River at km 143.5

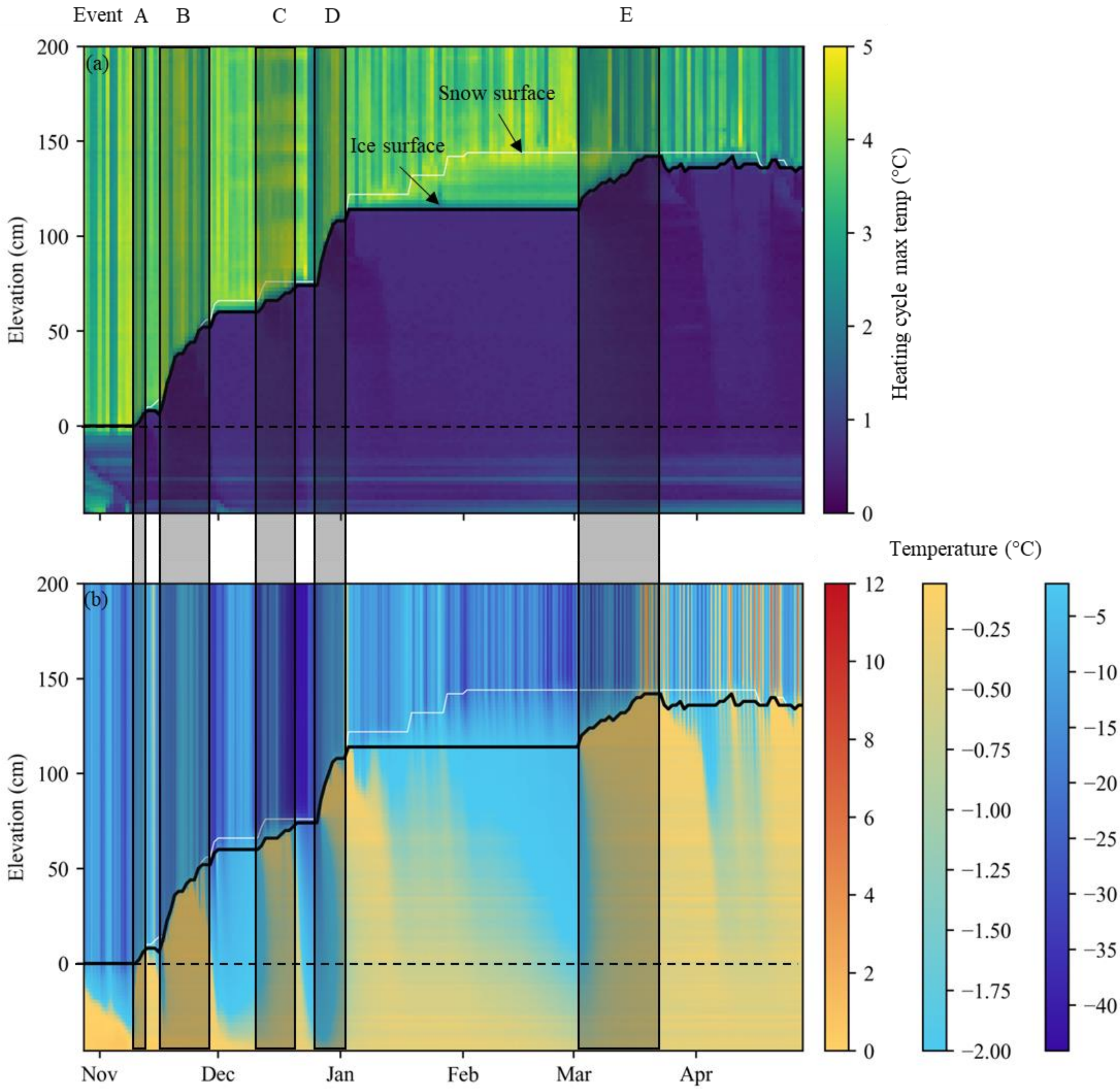

Figure 2. Temperature measurements along the SIMBA chain (a) after 120 sec of heating (i.e. heating cycle max temperature), and (b) without heating. Both show the approximate elevation of the ice (black) and snow (white) surfaces.

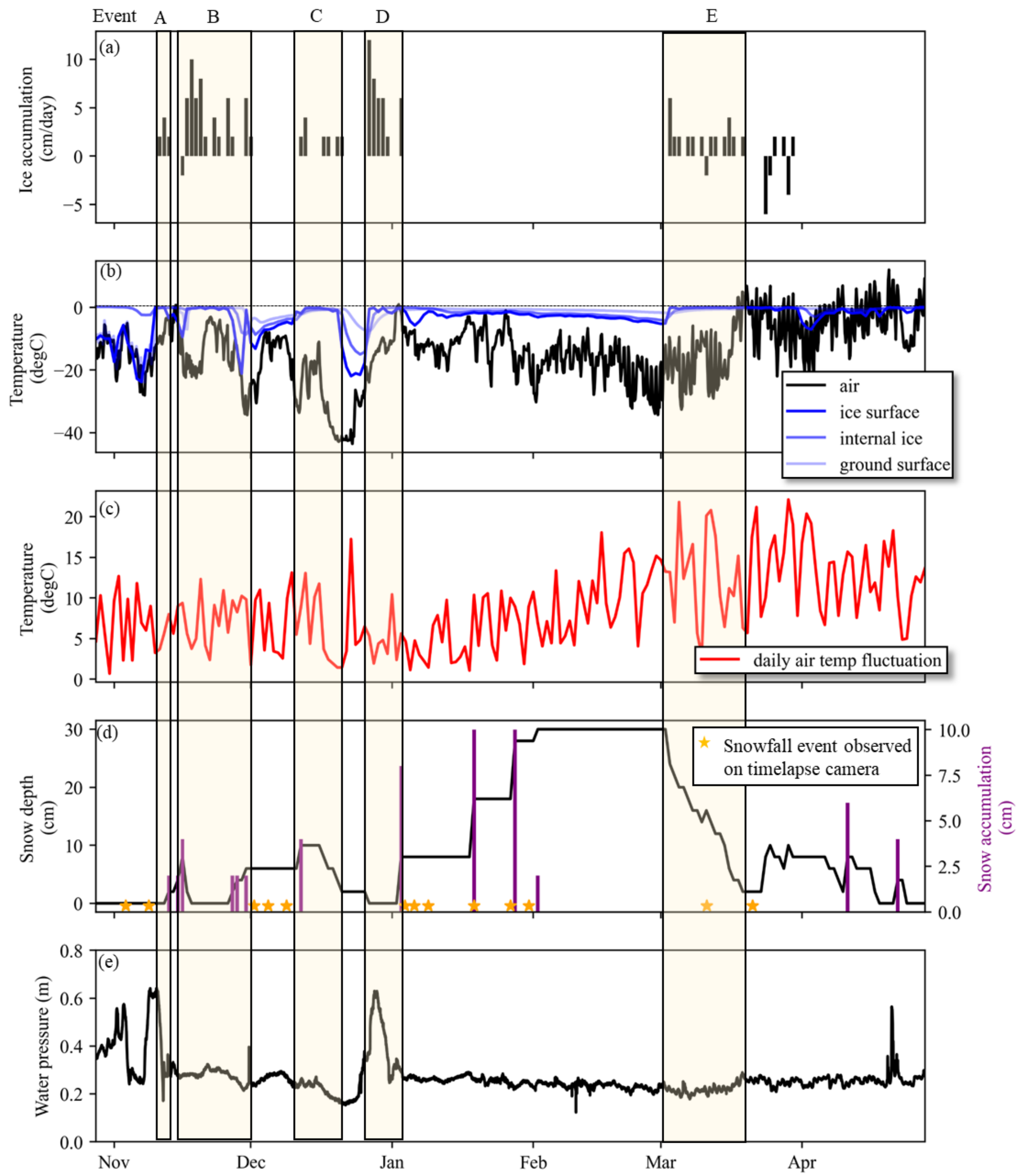

Figure 3. Timeseries at the SIMBA of (a) daily vertical ice accumulation (b) air, ice surface, internal ice (30 cm below the ice surface) and ground surface temperature, (c) daily air temperature fluctuations, and the temperature gradient in the ice (i.e. ice surface temperature minus the internal ice temperature), (d) snow depth as shown in Figure 2, as well as the discrete daily snow accumulation events derived from snow depth profile, and snowfall events observed from the timelapse cameras, and (e) water pressure, derived from a pressure sensor and corrected for atmospheric pressure.

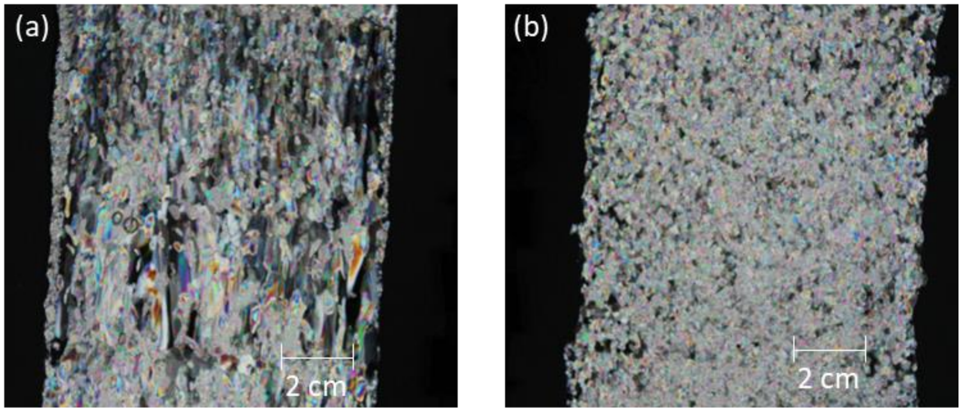

Figure 4. Polarized photographs of vertically oriented thin sections of the aufeis formed during (a) event D, in the absence of snow and (b) event E, in the presence of snow.

Acknowledgments

We respectfully acknowledge that this research was conducted on the traditional territories of the Tr'ondëk Hwëch'in and Na-Cho Nyäk Dun. This research was was financially supported by Transport Canada National Trade Corridors Fund (NTCF; Grant #164310). This report reflects the views of the authors and not necessarily those of Transport Canada. We thank Yukon Government Department of Highways and Public Works, including the staff at the maintenance staff at the Klondike Highway Camp, km 67 on the Dempster Highway.

References

Alekseev VR. 2016. Long-term variability of the spring taryn-aufeises. *Ice and Snow* **56**: 73–92 DOI: https://doi.org/10.15356/2076-6734-2016-1-73-92

Brasseur P, Kokelj S V, Fraser R, Lacelle D. NWT Open Report 2016-010 A first approximation of aufeis distribution in eastern Yukon and adjacent Northwest Territories, Canada

Carey KL. 1973. Icings developed from surface water and ground water. Hanover.

Ensom T, Makarieva O, Morse P, Kane D, Alekseev V, Marsh P. 2020. The distribution and dynamics of aufeis in permafrost regions. *Permafrost and Periglacial Processes* **31** (3): 383–395 DOI: 10.1002/ppp.2051

Grey BJ, MacKay DK. 1979. Aufeis (overflow ice) in rivers. In *Canadian Hydrology Symposium: Cold Climate Hydrology.* National Research Council: Ottawa; 134–165.

Heginbottom JA, Dubreuil MA, Harker PA. 1995. National Atlas of Canada.Ottawa, Canada.

Huryn AD, Gooseff MN, Hendrickson PJ, Briggs MA, Tape KD, Terry NC. 2021. Aufeis fields as novel groundwater-dependent ecosystems in the arctic cryosphere. *Limnology and Oceanography* **66** (3): 607–624 DOI: 10.1002/lno.11626

Jackson K, Wilkinson J, Maksym T, Meldrum D, Beckers J, Haas C, Mackenzie D. 2013. A novel and low-cost sea ice mass balance buoy. *Journal of Atmospheric and Oceanic Technology* **30** (11): 2676–2688 DOI: 10.1175/JTECH-D-13-00058.1

Kane DL. 1981. Physical mechanics of aufeis growth. *Canadian Journal of Civil Engineering* **8**: 186–195

Kane DL, Slaughter C. 1973. Seasonal regime and hydrological significance of stream icings in Central Alaska. In *Role of Snow and Ice in Hydrology: Proceedings of the Banff Symposia.* International Association of Hydrological Science; 528–540.

Kuhn M. 1987. Micro-Meteorological Conditions for Snow Melt. *Journal of Glaciology* **33** (113): 24–26 DOI: 10.3189/S002214300000530X

Li S, Benson C, Shapiro L, Dean K. 1997. Aufeis in the Ivishak River, Alaska, mapped from satellite radar interferometry. *Remote Sensing of Environment* **60** (2): 131–139 DOI: 10.1016/S0034-4257(96)00167-8

Makarieva O, Nesterova N, Andrew Post D, Sherstyukov A, Lebedeva L. 2019. Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost. *Cryosphere* **13** (6): 1635–1659 DOI: 10.5194/TC-13-1635-2019

Morse PD, Wolfe SA. 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. *Journal of Geophysical Research: Earth Surface* **120** (9): 1670–1686 DOI: 10.1002/2015JF003534

Stockton EG, Burn CR, Idrees M,, Calmels F. 2019. Monitoring Ground Temperatures in Permafrost along the Dempster Highway, Yukon and NWT. In *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, Bilodeau J-P, , Nadeau DF, , Fortier D, , Conciatori D (eds).Quebec City.

Terry N, Grunewald E, Briggs M, Gooseff M, Huryn AD, Kass MA, Tape KD, Hendrickson P, Lane JW. 2020. Seasonal Subsurface Thaw Dynamics of an Aufeis Feature Inferred From Geophysical Methods. *Journal of Geophysical Research: Earth Surface* **125** (3) DOI: 10.1029/2019JF005345

Turcotte B, Nafziger J. 2021. Detailed Interpretation of River Ice Processes in Water Level Time Series. In *CGU HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers*Saskatoon, SK.

Turcotte B, Dubnick A, McKillop R. 2023a. Icing and aufeis in cold regions II: consequences and mitigation. *Canadian Journal of Civil Engineering*

Turcotte B, Dubnick A, McKillop R, Ensom T. 2023b. Icing and aufeis in cold regions I: the origin of overflow. *Canadian Journal of Civil Engineering*

Turcotte B, Nafziger J, Clark S, Beltaos S, Jasek M, Alfredsen K, Lind L, Stander E. 2017. Monitoring river ice processes: Sharing experience to improve successful research programs. In *GU HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers.*Whitehorse.

Wankiewicz A. 2011. Analysis of winter heat flow in an ice-covered Arctic stream. *Canadian Journal of Civil Engineering* **11** (3): 430–443 DOI: 10.1139/L84-064

Wanty RB, Wang B, Vohden J, Day WC, Gough LP. 2007. Aufeis Accumulations in Stream Bottoms in Arctic and Subarctic Environments as a Possible Indicator of Geologic Structure Recent U.S. Geological Survey Studies in the Tintina Gold Province, Alaska, United States, and Yukon, Canada-Results of a 5-Year Project

Water Resource Branch D of Environment. 2023. Yukon Snow Survey Bulletin and Water Supply Forecast

Wrangel FP. 1841. *Journey along the northern coast of Siberia and along the Arctic Sea in 1820--1824. St. Petersburg, Russia: The expedition under the command of the navy lieutenant FP Wrangel*.

Yoshikawa K, Hinzman LD, Kane DL. 2007. Spring and aufeis (icing) hydrology in Brooks Range, Alaska. *Journal of Geophysical Research: Biogeosciences* **112** (4) DOI: 10.1029/2006JG000294

Yoshikawa K, Petrone K, Hinzman LD, Bolton WR. 1999. Aufeis development and stream baseflow hydrology in the discontinuous permafrost region, Caribou Poker Creek Research Watershed, Interior Alaska. In *Program and Abstracts*, *50th Arctic Science Conference,19–22 September 1999.* American Association for the Advancement of Science Arctic division: Fairbanks; 202–203.