



Exploring the benefits of an ice-adapted ferry at Dawson – Yukon River ice conditions assessment

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Executive Summary

The Department of Highways and Public Works, Government of Yukon, is exploring different options to replace the aging George Black Ferry. This study emphasizes the option of a free-running (propeller) ice-adapted ferry that could operate in moderate ice runs in the fall and light ice runs in the spring. Gains in the duration of the ferry season are explored from an historical (2005-2025) and climate change (2030-2060) perspectives. Some theory and observations about ice formation and breakup processes on the Yukon River at Dawson are presented, and a simple river ice formation model is developed and described to support the assessment.

Results:

- Under current conditions, the ferry season lasts 153 days, on average (May 15 to October 15).
- An ice-adapted ferry could potentially lead to an extended ferry season of 188 days, on average (May 6 to November 9, representing an additional 35 days).
- If a new vessel similar to the George Black Ferry was proposed and if its operation was closely informed by accurate ice forecasts, its season could extend over 172 days (October 22 to May 10, an additional 19 days compared to the current situation).
- Climate change could extend the ferry season by 7 days by 2060 (3 days in the fall, 4 days in the spring). This, however, is based on a rather simple assessment.

The discussion section of this report proposes a couple of recommendations:

- Share this report with engineers who would propose/evaluate final design options to replace the George Black Ferry (occurred in May 2026).
- Create a multidisciplinary team composed of local knowledge holders, river engineers, river ice specialists, and ship designers, to inform the final ferry design and operation conditions, considering the federal regulation context.

Other topics of interest that are influenced by ice processes in the Yukon River include a cabled-ferry option and the construction of permanent ferry landing structures. The possibility for an ice-adapted ferry to actively improve freeze-up conditions at Dawson, therefore supporting the preparation of an ice bridge, should also be further explored.

Future steps for this work are presented in the discussion section.

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1. Introduction

1.1 Context

The George Black Ferry has been transporting people, vehicles, and goods across the Yukon River at Dawson in central Yukon since the 1960s. The aging vessel is becoming less reliable and more costly to maintain and repair. In a context where the construction of a proper bridge to replace the ferry (and the ice bridge in winter) has been left aside, the Department of Highways and Public Works, Transportation Engineering Branch (HPW-TEB), has no other choice but to initiate a ferry replacement project. Several questions need to be answered to converge on an optimized, cost-effective ferry design linking the North Klondike Highway (Highway 2) and the Top of the World Highway (Highway 9). Among the characteristics that the new ferry could possess, cabled and ice-breaking ferry options are being explored (e.g., 3GA Marine Ltd, 2024).

The YukonU Research Centre, Climate Change Research Group (YRC-CCR), completed a study of the dynamics of ice cover formation (i.e., freeze-up sequence) on the Yukon River near Dawson (Turcotte, 2020). The same research group has been developing river ice breakup forecasting models for the Yukon River in more recent years (Turcotte et al., 2024). The YRC-CCR believes that the ferry season, generally corresponding to the open water (ice-free) season, could be extended by a few weeks in the fall and by a few days in the spring if the new ferry were adapted to navigate in drifting ice conditions and if border ice at both ferry landings were managed. Quantifying the gain in the ferry operation period may justify a more significant investment in the future vessel. In the absence of detailed, systematic records of daily ice conditions during shoulder seasons over several consecutive years, determining the annual gain in the ferry season under current and future climate conditions requires a study that involves the development of a simple freeze-up simulation model.

1.2 Premise of this report

The authors of this report believe that operating a ferry during the entire winter season (the ice-breaking ferry option, as briefly described and commented by Robert Allan Ltd., 2024 and Morrison Hershfield, 2024) on the Yukon River near Dawson:

- Is nearly impossible from a technical perspective due to the hydroclimatic (thermal and mechanical aspects of river ice represent substantial constraints) and bathymetric (too shallow for the hull of an ice-breaking vessel) contexts.
- Is likely difficult to justify financially, given the current and foreseeable socio-economic context (too expensive to design, build, and operate) relatively to the intensity of ice processes and cold conditions the ferry and its crew would face.
- Would be challenging from a regulatory angle.

A cabled ferry option, explored by 3GA Marine Ltd. (2024) and presenting obvious energy efficiency benefits, could be considered to replace the current, free-running George Black Ferry. However, beyond the cable potentially rusting over time, the need to remove large woody debris that could get caught by the underwater cable (especially during and after high flow events), the cable would also need to be removed before significant border ice forms and reinstalled once spring breakup is over. These elements could translate into a shorter ferry season.

A permanent aerial cable option would potentially reduce maintenance costs while keeping the energy-efficiency aspect of a guided ferry, but it would present the following limitations:

- The cable anchors on both shores would require a significant investment (the cable would need to remain relatively high above the water surface to avoid interfering with local navigation, including large barges, which implies a combination of tall anchor towers and significant cable tension).
- The cable could interfere with float plane traffic.
- The infrastructure could have a negative aesthetic and safety impact.

The author of this report proposes to explore another ferry alternative to replace the George Black Ferry: an ice-adapted ferry, a free-running vessel that could operate in partial ice conditions. The main advantage of this option would be to extend the ferry season in the fall (by a few weeks) and in the spring (by a few days). During winter months, the ice bridge would remain the main option for crossing the Yukon River near and at Dawson (even if climate change leads to a gradually shorter ice bridge season; Tetra Tech, 2017).

Freeze-up scenarios leading to the presence of a resilient open water lead or thin ice in front of Dawson, a process explained in Section 3.1, are apparently becoming more frequent: This happened in the fall of 2013, 2016, 2017, 2018, 2023, and 2025, which translates into a recent annual probability just short of 50%. This early-winter ice condition at the normal ice bridge location delays or simply prevents the preparation and certification of an ice bridge. In such situations, an ice-adapted ferry could present significant benefits. First, it could be possible to operate this ferry in open water on some (warmer) days during the cold season. This operation, however, would need to consider the following conditions:

- Water would freeze against the hull at a rate roughly proportional to the air temperature. Therefore, some heating may be needed to maintain the vessel's hydrodynamics.
- Border ice would form at both ferry landings/ramps at a rate that would also be proportional to the air temperature. The mechanical removal of a newly formed stationary ice cover from the shore may be required on a daily basis, especially during/after cold spells.
- Frost could accumulate on the deck, railings, and other exposed features of the ferry in cold and humid air. The accumulation rate of those crystals would depend on air temperatures, as well as on wind and humidity conditions.
- Safety of the crew and passengers would remain a concern despite the absence of drifting ice slush and floes in the flowing water.
- Regulation may prevent operating a vessel in cold conditions.

Second, if one turns that open-water scenario around, a new ferry adapted to navigate ice-infested waters could travel upstream to the Klondike River delta and mechanically break a recently formed (and partially consolidated) ice congestion to keep the ice run flowing past Dawson. This intervention would significantly increase the probability of seeing the formation of a complete ice cover in front of Dawson in the following hours or days, just by allowing the early-winter ice run to "fill up the open water gap". The success of such an operation would not be guaranteed; it would need to be done in the hours following the interruption of the ice run. The frequency of Klondike River delta freeze-up scenarios in recent years may justify this type of investment and the need for this uncommon operation, especially if the ferry is already adapted to moderate ice run conditions.

Generally, it is anticipated that the main challenges associated with operating an ice-adapted ferry during ice runs would be 1. To manage the ice that would form around and under the hull during cold spells and cloud-free evenings/mornings, 2. To remove border ice (up to 0.3 m-thick after a cold night) to set the ferry free from its night-time frozen state, 3. To anticipate the optimal timing to pull the ferry back on shore before winter settles, and 4. To keep the engines running in cold temperatures. This would also depend on 5. Current navigation regulation.

2. Objectives

The objectives of this study are:

- Summarize knowledge about ice conditions during the freeze-up and breakup periods on the Yukon River at Dawson.
- Quantify the possible duration of an extended ferry operation period into partial ice conditions during the freeze-up period in current and future climate conditions.
- Evaluate the possible extension of an advanced ferry operation period into partial ice conditions during the spring breakup period.

3. Background

3.1 Ice conditions into winter (freeze-up)

This section of the report describes the transition from open water to stable ice cover conditions, which typically occurs between mid-October and late-November on the Yukon River near Dawson.

The following discussion refers to heat loss at different stages of ice development because heat loss is what triggers and controls ice formation. While heat loss should generally be expressed in terms watts-hours per square metre of channel ($W\text{-h}/m^2$), this parameter is not convenient to estimate because of its significant spatial and temporal variability. Parameters such as cumulative degree-days of freezing (CDDF, the sum of negative temperatures over time) or snowfall events, although they represent rather simple heat loss indicators, are more accessible, as will be described later in this report.

Pre-freeze-up period

No ice forms in a river as long as its water temperature (T_w) does not drop to 0°C . Consistent subfreezing air temperatures (T_{air}) are therefore required for several days to extract the heat carried by the flow and stored in wetlands, groundwater, and the riverbed. The amount of heat loss to bring T_w down to freezing conditions depends on the initial (fall) T_w . The state of the Yukon River channel immediately before the ice season is presented from a satellite perspective in Figure 3.1.1.a.

It is possible to see some border ice forming at shallow and slow-flowing locations along the banks of the river (including some secondary channels) during the first late-fall cold days, even if T_w in the center of the channel is slightly above 0.0°C . This is because this stagnant water does not mix with the warmer water from the fast-flowing environment. This ice cover, however, usually remains thin (a few centimetres) until additional heat loss occurs.

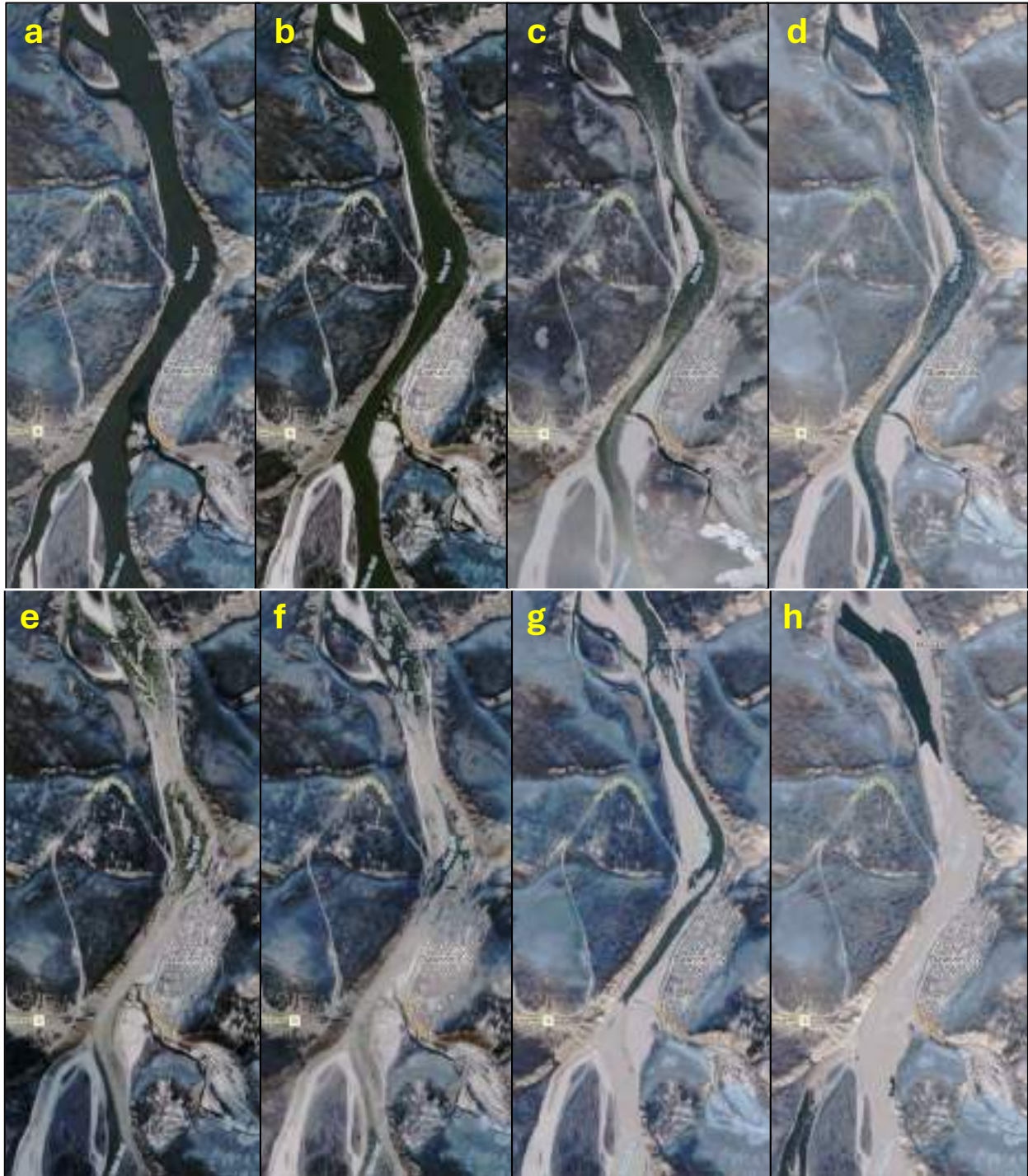


Figure 3.1.1. Sample of eight Sentinel 2 satellite images of the Yukon River at Dawson with different freeze-up conditions. *a. No ice, b. Light ice run from the Klondike River, c. Light to moderate ice run, d. Moderate ice run, e. Intense ice run with moderate consolidation, f. Intense ice run and significant consolidation, g. Post freeze-up condition with a Klondike River delta congestion, h. Post freeze-up condition with a Moosehide congestion. A normal freeze-up process may involve several weeks of changing partial ice conditions, alternating between states c and f. Credit: European Union – Copernicus Sentinel Data 2026.*

Freeze-up onset

Once T_w in the Yukon River drops to 0.0°C (or slightly below, a state called “supercooling”), two common forms of ice will co-occur: (drifting) ice crystals are produced in the fast-flowing (mid-channel) environment, and (stationary) border ice extends from the channel bank towards the fast-flowing environment. For more on this topic, readers are invited to consult Beltaos (2013).

Ice crystals, called frazil, form in moving water at a rate proportional to heat loss at the river surface, which can be correlated with some confidence to T_{air} . The resulting slush will drift downstream and tend to float at the water surface. Frazil could also be momentarily entrained back under the water surface in turbulent (i.e., fast-moving flow) areas of the Yukon River. This entrainment often occurs at channel bends, where the flow tends to rotate sideways in a spiral shape (clockwise for left bends when looking downstream). Frazil crystals are initially “active”, which means that they can stick to one another by quickly developing freezing bonds. Therefore, over time (and with increased travel distance), this frazil slush will agglomerate into small frazil flocs and then into larger ice pans. Under a positive heat budget (e.g., once the sun is up and if T_{air} is above -10°C , or so), the frazil will not immediately start to melt as it contains a significant heat deficit from its latent heat of fusion (a physical property). However, it will become “passive”, which means that its sticky properties will be lost. This could mean that frazil pans fracture when they collide. However, these pans could remain intact or even fuse together because of cohesion, a linkage promoted by lateral compression (e.g., in a narrowing channel segment). Freezing links between flocs and pans generally form faster in mountain-shaded areas or at night under clear-sky conditions.

Snow falling in the water whose temperature is close to freezing will generate an ice run which aspect compares with that of frazil slush, and snow slush also presents cohesive properties. During the first stage of freeze-up, frazil runs are usually light (Figure 3.1.1.b) or moderately intense (Figure 3.1.1.c-d). They are formed of small ice pans of limited thickness, they do not cover a significant portion of the channel surface, and they can be interrupted by warmer (not necessarily melting) weather.

Border ice is a stationary form of surface ice. Under cold conditions, and once T_w drops to 0.0°C , this surface ice will inexorably form in slow-flowing (i.e., potentially thermally stratified) locations along the Yukon Riverbanks. Border ice can initially be formed from arrested frazil pans that fuse, or simply by the growth of thermal ice crystals that migrate horizontally (sideways) from the bank. These crystals, known as skim ice, can form an ice cover relatively quickly in stagnant water, such as in bays, near eddies, and behind islands. As the ice edge migrates laterally and comes into contact with a faster-flowing environment, the passive or thermal freeze-up process slows, and it can transition to a more dynamic process that involves the “recruitment” of drifting, active frazil crystals and flocs that rub against it. This creates an ice cover with a rougher surface, characterized by a series of linear ice crests parallel to the flow. A V-shaped ice cover can form following this exact process at the upstream tip of islands. Generally, for a given cold T_{air} , the faster the flow, the slower the border ice migrates towards the middle of the channel. This means that a high discharge during the freeze-up period should delay the formation of border ice and the overall freeze-up process. In the Yukon River near Dawson, border ice rarely occupies more than 20% of the channel surface before a more dynamic and complete freeze-up occurs.

Ice congestion

At some point during the freeze-up period, once T_{air} consistently drops below -10°C , the frazil run becomes heavier (denser and thicker), increasing the ice concentration at the water surface. This is because hundreds of river kilometres upstream of Dawson, including tributaries, are losing heat and consequently producing ice crystals. In parallel, the presence of border ice and the declining flow create opportunities for the ice run to be laterally compressed (choked) at distinct narrow locations. This hydromechanical compression process will result in the thickening and (temporary or lasting) fusion of ice pans, as well as a reduction in the surface concentration of the ice run downstream of these narrows, thereby promoting greater heat loss between the water and the air. It is anticipated that the degree of consolidation (combining freezing and compression-cohesion links) of the ice runs in narrows depends on:

- The incoming ice concentration,
- The width reduction ratio of the channel,
- The rate of heat loss (or T_{air}).

Figures 3.1.1.e-f present examples of how the ice run reaching Dawson is first laterally compressed by the Klondike River delta narrow. It then reaches the wider Ferry crossing channel segment before entering a second narrow section just upstream of Moosehide (or in front of the Yukon River Campground). Larger ice rafts (made of fused frazil pans) exit these narrows and become fractured downstream, probably because of the presence of turbulent flow conditions (i.e., waves).

Interestingly, as pointed out by Turcotte (2020), the main narrows of the Yukon River where the ice run becomes significantly compressed are located:

- 100 km downstream of Dawson (20 km downstream of the Forty Mile River),
- At Moosehide (less than 5 km downstream of Dawson),
- At the Klondike River delta (just a few km upstream of Dawson),
- 120 km upstream of Dawson (White River confluence).

In other words, over 220 km of the Yukon River, there are four significant narrows, two of which are located immediately upstream and downstream of Dawson. These narrows are precisely where, in most winters, the ice run becomes compressed, enough to slow and stop. This process, known as the “congestion process” or “freeze-up jam initiation”, usually occurs when the daily-averaged T_{air} is below -20°C (Turcotte, 2020) or after a snowfall (Nagano, pers. com., 2025).

The ice run’s congestion causes backwater (water that piles up behind it), thereby storing significant potential energy. If this energy rises too quickly, the congestion is followed by a dynamic release, which creates a small surge and a condensed ice run. However, at some point, the newly formed congestion freezes in place, and the upcoming ice run is arrested upstream behind it, leading to the formation of a complete ice cover over long distances in a few days (a process called “frontal progression”). For instance, a significant ice run can generate a bank-to-bank ice cover over more than 30 km of the Yukon River within 24 hours. Generally, the recently formed ice cover will be thicker and present a rougher surface (i.e., a consolidated ice cover) in narrower segments where significant lateral compression and upstream-to-downstream pushing will have occurred. In contrast, the ice cover will be smoother in wider river segments.

A persistent open-water area usually remains downstream of freeze-up jam initiation locations, which explains why there was no ice cover in front of Dawson during several recent winters: the

congestion location was the Klondike River delta (Figure 3.1.1.g). In most years, congestion occurs at Moosehide or downstream, and the ice cover is completed in front of Dawson (Figure 3.1.1.h).

Once insulated by an ice cover upstream of Dawson, the Yukon River no longer produces frazil, and the freeze-up period is considered to be over. Areas that remain open will generally form an ice cover through gradual border-ice migration and slush accumulation at the downstream edge during the winter. Some areas, representing less than 1% of the channel surface over hundreds of kilometers, will remain free of ice for the entire winter. That small 1% is occasionally concentrated into a higher ratio just in front of Dawson due to the nearby congestion point.

3.2 Ice conditions at the end of winter (spring breakup)

The breakup regime of the Yukon River near Dawson has been described in a recent report (Turcotte et al., 2024) that introduces and explains a new river ice breakup forecast model intended for use by the Government of Yukon, Department of Environment. The exact definition of spring breakup may vary across populations and within the community of cold-region hydrologists. The textbook definition of spring breakup (e.g., Beltaos, 2008) includes the initial period of ice cover deterioration induced by solar (shortwave) radiation and by warm T_{air} before the ice cover fractures and mobilizes. However, the common and convenient definition of river ice breakup is the first sustained movement of the local ice cover in the downstream direction. This movement can 1. Be immediately followed by the formation of an ice jam upstream or downstream of the ice bridge or, 2. Lead to the complete clearance of the ice cover over 10s of river kilometers downstream of Dawson. In most years, superimposed ice slabs and compacted slush will be left along the banks of the river. These “shear walls” (with a vertical face on the river side indicating the boundary between the arrested and the moving ice, or ice run) are generally in the order of 1 to 3 m-high, a thickness proportional to the intensity of the breakup event. These walls may prevent access to the river until they melt in place or are gradually dismantled by the rising river flow.

The clearance of the ice cover in front of Dawson does not mean that the “ice season” is over. Looking downstream, it is possible that the ice of the Yukon River that was originally sitting in front of Dawson forms a moderate or a major ice jam between Moosehide and the Forty Mile River for up to a week. This only means that the water level will be higher at Dawson than it would be without this flow obstruction, but it does not represent a concern to navigation across the Yukon River. In the upstream direction, however, remaining ice jams near Sweed Creek, the Indian River, the Sixty Mile River and even the White River, or ice runs originating from the Stewart River, may transit through the Dawson reach of the Yukon River in the following hours to days. These ice runs may be relatively light (Figure 3.2.1a) or moderate (Figure 3.2.1b) but are often intense (Figure 3.2.1c), especially when they result from the release of a nearby (<50 km) ice jam.

Based on observations over recent years, it appears that there are about 3-6 hours of continuous, high-intensity ice runs passing in front of Dawson after the mobilization of the local ice cover. In some years, it is this main ice run that triggers local breakup, whereas in others, the high-intensity ice run reaches Dawson a few hours to a couple of days later. In 2022, the main ice run traversed the Dawson segment of the river one day after the ice cover had been mobilized, as presented in Figure 3.2.2. This ice run was accompanied by a 2 m-high surge that also lasted several hours.



Figure 3.2.1. Sample of three Sentinel 2 satellite images of the Yukon River with different spring breakup ice run intensities. a. Light ice run with dispersed ice floes at Dawson, b. Moderate ice run with a relatively high ice concentration at Dawson, c. Full concentration ice run near the Sixty Mile River upstream of Dawson. Credit: European Union – Copernicus Sentinel Data 2026.



Figure 3.2.2. Three photos taken by an automated camera installed at Water Survey of Canada station 09EB001 on the Yukon River at Dawson. a. Open water condition with minor shear walls on the morning of May 8, 2022, b. Ice run on the afternoon of May 9, 2022, c. Open water condition with significant shear walls on the evening of May 9, 2022. Credit: Environment and Climate Change Canada.

3.3. Examples of ferries operating in cold regions

This last portion of the background section presents a sample of different ferries operated in cold regions. Table 3.3.1 summarizes this information. Readers will note that ferries that offer a winter service are generally operated in more temperate regions and may still require the support of proper ice breakers (i.e., during cold spells). Most small ferries cannot operate in heavy ice runs.

Ferry name	River/Lake	Crossing distance	Length of vessel	Ferry type	Draft	Year built	Min winter temp.	Winter intensity	Winter operation
George Black	Yukon River at Dawson	420 m	25 m	Propeller	1.23 m	1967	-50°C	3200°C-days	No
M.V. Louis Cardinal	Mackenzie River & Arctic Red River	1900 m	38 m	Propeller	2.2 m	1972	-48°C	4300°C-days	No*
M.V. Abraham Francis	Peel River	300 m	24 m	Cable	1.6 m	1981	-48°C	4250°C-days	No
M.V. Lafferty	Liard River, Fort Simpson	650 m	39 m	Propeller	0.95 m	1993	-44°C	2850°C-days	No
M.V. Johnny Berens	Mackenzie River, N'Dulee	1150 m	24 m	Propeller	1.6 m	1961	-44°C	2950°C-days	No
N.M. Alphonse-Desjardins and N.M. Lower-Gouin	St. Lawrence River, Quebec	1000 m	64 m and 61 m	Propeller	3.85 m	1971	-28°C	920°C-days	<u>Yes**</u>
M.V. Jos-Deschênes II and M.V. Armand-Imbeau II	Saguenay River, Tadoussac	1450 m	87 m	Propeller	4.5 m	2018	-18°C	720°C-days	<u>Yes</u>
Paule II	Des Prairies River, Montreal	110 m	~14 m	Cable (aerial)	small	1987	-22°C	675°C-days	No
Osprey 2000 and M.V. Balfour	Kootenay <u>Lake</u> , British Columbia	8800 m	~79 m	Propeller	2.7 m	2000 and 1954	-15°C	180°C-days	<u>Yes</u>
Usk	Skeena River	180 m	~13 m	Cable	small	~1981	-20°C	280°C-days	No
Sugar Islander II	St. Marys River, Michigan	380 m	32 m	Propeller	2.0 m	1995	-28°C	775°C-days	<u>Yes**</u>
Lautta #191	Koivukanta, Finland (<u>Lake</u>)	720 m	36 m	Cable	2.4 m	2011	-25°C	850°C-days	<u>Yes***</u>

* A video online seems to show the M.V. Louis Cardinal in winter moving within a narrow channel made by an excavator operating from the ferry's deck. However, in winter, an ice bridge usually supports winter transportation across the Mckenzie River and Arctic Red Rivers.

** May need the support of an ice breaker during cold spells.

*** Pictures show this ferry operating during the winter months in a channel located next to an ice bridge. Winters there are relatively mild.

4. Methodology

This report examines the possible gain, in terms of service days per year, of operating an ice-adapted ferry at Dawson to replace the aging George Black Ferry. This implies a quantitative description of partial ice conditions. Between open water and complete ice cover conditions, partial ice conditions can be described based on three criteria:

- Border ice ratio (B) at the ferry crossing.
- Frazil, snow slush, or ice run concentration (CT).
- Frazil, snow slush, or ice run consolidation (CD).

Parameters B and CT strongly influence on the frazil run consolidation (CD) because flowing ice is laterally compressed as it flows through a border-ice-constricted segment. However, the ferry segment of the Yukon River is generally wider (>300 m) than the border ice-constricted segments located at the Klondike River delta and near Moosehide (150 m), as described in Section 3.1. The surface ice run concentration (CT) at the ferry crossing is generally lower because flowing ice pieces are probably thicker. Since B generally evolves gradually during the first cold weeks of winter and because its impact on freeze-up is captured by CD, B can be excluded from a model that simulates ice conditions in a navigation perspective. However, border ice would still need to be managed for a ferry to operate in partial ice conditions.

4.1. Quantification of the freeze-up ice run

The European Space Agency operates the Sentinel 1 and Sentinel 2 satellites, which capture images of the planet at a sub-weekly interval (2-4 images per week) at high resolution (about 5 m). Sentinel 1 provides radar (backscatter) type of products year-round, whose interpretation can be challenging, especially when the frazil ice run is light. However, it can see through the cloud coverage and therefore provides important complementary observations to those obtained from the visible, but occasionally cloud-affected, imagery from Sentinel 2, which is only available until mid-November.

The discontinuous ice run, beginning in early October and ending once freeze-up is complete, was classified using these satellite products. Each available image was manually analyzed to obtain a quantitative estimate of the ice run concentration (CD). This approach was more convenient than an automated method because of the limited number of useful images between 2016 and 2025, and the complexity of interpreting images partially affected by clouds. Since the freeze-up ice run usually changes gradually over time and distance (as opposed to breakup ice runs), it was considered adequate to develop a daily time-step model.

Five ice run conditions were distinguished, as presented in Figure 4.1.1:

- **0: Open water:** No visible drifting ice (Figure 4.1.1a-b).
- **1: Light ice run:** The ice run concentration (CT) would be lower than 30% of the channel surface at the ferry crossing without any visible consolidation (CD=0, No lateral slush compaction or consolidation, Figure 4.1.1c-d). Solid ice floes, if any, would be small (<1 m) and thin (<0.3 m). Based on simple ice volume and heat budget estimates, this means up to about 30 tons of ice and snow slush are transiting in the Yukon River every second. The frazil could be active (it would stick to a vessel's hull) after sunset and before sunrise, but it would likely become passive once the sun is up.

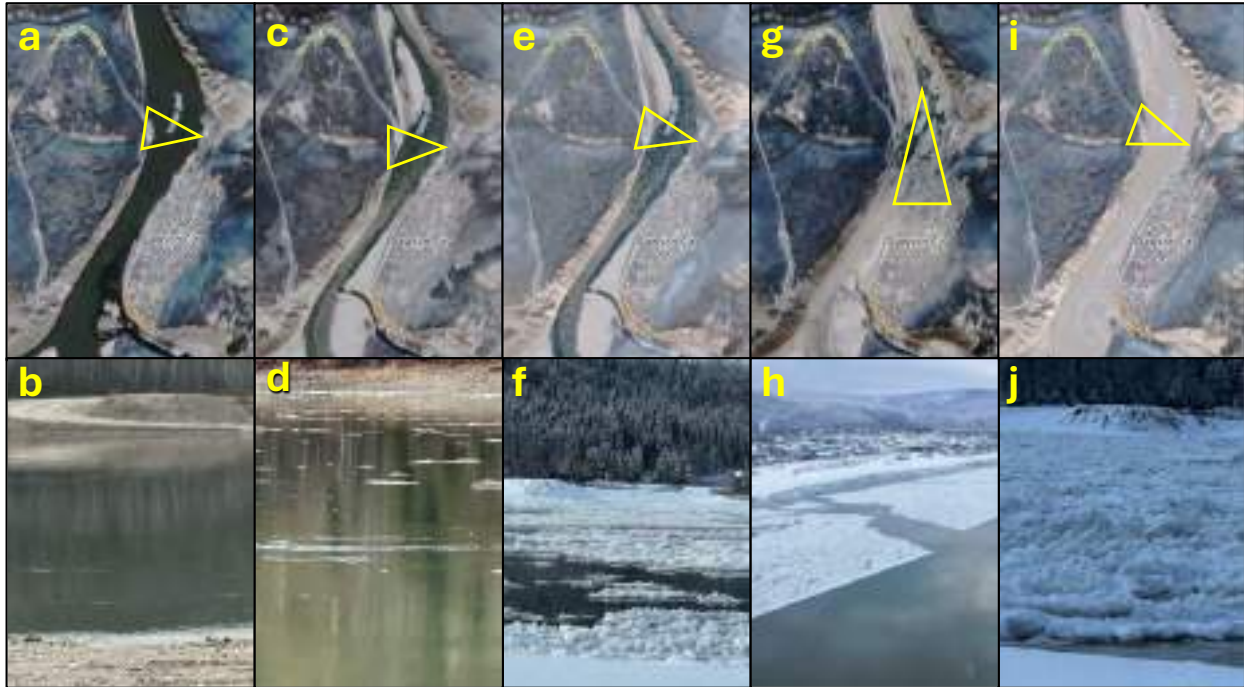


Figure 4.1.1. a-b. Open water conditions (0), c-d. Light frazil run (1), e-f. Moderate ice run (2), g-h. Intense ice run (3), i-j. Complete ice cover (4). Images presented in a, c, e, g, and i are from Sentinel 2 (Credit: European Union – Copernicus Sentinel Data 2026). Photos b, d, f, and j are credited to Simon Nagano from Klondike H₂O. Aerial photo h is provided by The Department of Highways and Public Works, Government of Yukon.

- 2: Moderate ice run:** CT would be less than 70% with moderate consolidation (CD=1, most ice pan and frazil agglomerations would become fractured downstream of a channel constriction before they can freeze together, Figure 4.1.1e-f). Ice floes could be larger than 1 m and present a thickness of about 0.3-1.0 m, which corresponds to a maximum of 120 tons of ice per second. The frazil could be passive during daytime, but would likely be sticky most of the time, especially during dark hours and clear skies.
- 3: Intense ice run:** CT would be higher than 30%, and the ice run, composed of slush and larger ice floes, would be significantly consolidated. This means that large rafts, including solid ice slabs that offer a mechanical resistance to breaking, would flow across the ferry path, occasionally forming fractures (Figure 4.1.1g-h). The flow of ice would be essentially continuous in the middle of the Yukon River, at about 200 tons per second. There may be no drifting ice close to the banks, especially on the West Dawson side of the river (Figure 4.1.1h), but supercooling and an active frazil state would likely prevail. This ice run intensity would lead to the formation of a full ice cover on the Yukon River.
- 4: Complete ice cover:** The dynamic formation of the ice cover could travel relatively fast in the Yukon River, especially if condition 3 was observed after the occurrence of an ice run congestion. Once a consolidated ice cover had formed at the ferry crossing (Figure 4.1.1i-j), navigation would essentially become impossible for reasons stated in Section 1.2. A recently formed ice cover at Dawson could release (as in 2025), generally under relatively mild air temperatures. In this case, operating a ferry could become possible again. Also, if the post-freeze-up open-water lead remained at Dawson, it is conceivable that ferry operations could be maintained pending management of border ice, frost, and frazil accretion (Section 1.2).

To summarize, seven factors or conditions could affect the operation of an ice-adapted ferry during freeze-up:

- Border ice, affecting access to ferry landings and trapping the ferry at night.
- Active frazil sticking against the ferry's hull, or thermal ice forming around the hull at the water line and impacting the vessel's floatation and hydrodynamics.
- Intense ice runs (high CT) pushing against the ferry's hull during a crossing.
- Large, consolidated ice rafts (high CD) resisting to mechanical breaking.
- Frost forming on the deck, ramps, stairs, and rails.
- Cold temperatures affecting the ferry's mechanics.
- Heavy snowfalls and thick fog reducing visibility.

The hypothesis of this project is that the ferry could only operate in ice run conditions 0 to 2 and would need to be pulled out of the Yukon River before state 4 is achieved or before very cold weather conditions are expected. It would be possible to remove the ferry from the water during an ice run condition 3.

4.2. Simulation of the freeze-up ice run

Satellite products that enable the classification of ice run conditions (1 to 3, as described in the previous section) on the Yukon River for the period of 2016-2025 could not be used to reconstruct continuous freeze-up sequences. However, satellite imagery could support the development and calibration of a simple, empirical (multi-threshold) freeze-up model that relies on accessible hydrometeorological data. The model was calibrated using data and observations from 2021 to 2025, tested on the period 2016-2020, and then used to reconstruct freeze-up sequences for the period 2005-2016 (before the Sentinel 1 and Sentinel 2 era). The model could also explore future (2030-2060) freeze-up conditions using expected weather conditions supplied by the Government of Yukon.

Factors that directly control heat fluxes (and therefore water-cooling and ice-production rates) and hydrodynamic conditions are impractical to monitor continuously. Therefore, indicators of those factors were selected, considering the accessibility to historical data and the possibility of extracting simple weather data from a future climate simulation. Based on experience, past publications (e.g., Turcotte, 2020), and local knowledge, the following parameters were selected:

- Air temperature (T_{air})
- Cumulative degree-days of freezing (CDDF)
- Precipitation (or changes in snowpack thickness)
- Flow condition departure from the historical average in the Yukon River during freeze-up and the following winter

Figure 4.2.1 describes the model. In summary, the model links the current (T_{air} or recent days) and cumulative coldness (CDDF) with ice run intensities described in Section 4.1. This is shown in the table located in the middle of Figure 4.2.1 with different thresholds. Two parameters add to the complexity of the table and are meant to consider year- or event-specific observations derived from satellite products:

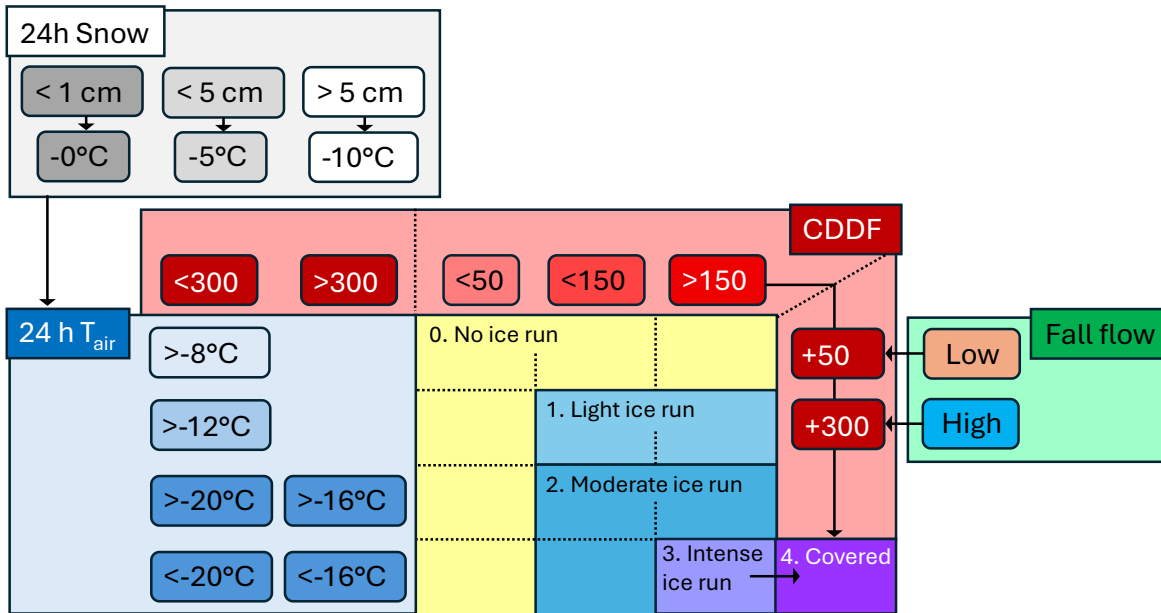


Figure 4.2.1. Diagram explaining the different thresholds of the model to identify which ice run condition (0 to 4) prevails in the Yukon River at Dawson. All the weather data is obtained from the Environment and Climate Change Canada weather station at Dawson. Snowfalls impose a modification of the daily-averaged air temperature whereas the flow of the Yukon River delays the transition from the first intense ice run (3) to a full ice cover (4).

- Snowfall is known to add ice crystals to flowing water. Therefore, solid precipitation near Dawson, derived from daily-averaged precipitation measurements or from variations in snowpack thickness, was included in the model as a cooling factor. For instance, as described in the grey box in Figure 4.2.1, more than 5 cm (informed by calibration) of snow in 24 hours would affect the ice run to a similar extent as if T_{air} were 10°C cooler.
- It was observed that the flow of the Yukon River could influence the timing of freeze-up congestion. Although the signal remains unclear because of the limited size of the calibration data set, it seems that when the flow is much higher than normal during the freeze-up period, the formation of a first freeze-up congestion and the consequent formation of a complete ice cover is delayed by several days, or in the case of the model, by several cool days, or CDDF. This explains why it would require 300 rather than only 50 additional °C-days of freezing to reach the ice condition 4. Figure 3.7 from a Tetra Tech (2017) report suggests that higher flows in the fall would delay the opening of the ice bridge, which, by continuity, can be interpreted as a delay in the formation of a complete ice cover.

Readers will also note that once more than 300°C-days of freezing are cumulated, the threshold for an intense ice run drops from a daily T_{air} of -20°C to -16°C, likely because the water has had ample time to cool to 0°C throughout the drainage system. It is also possible that the need for this additional threshold arises from a lower sun angle and shorter days, which are usually correlated with cumulated coldness.

Once the model was calibrated, tested, and adjusted (results presented in Section 5), it was applied to historical weather (2005-2015) and hypothetical future weather (2030-2060) following a carbon emission scenario SSP3-7.0 (not as pessimistic as the high emission scenario SSP5-8.5, but not an optimistic scenario either). Future flows could not be obtained as this would require running a fully

calibrated, Yukon River watershed-scale hydrological model. In this case, the authors simply assumed that when cumulative precipitation at Dawson between July and October would be much higher than usual, flows in the Yukon River would likely be high as well. Of course, the Yukon River drains most of the Yukon and part of British Columbia, whereas Dawson only represents a small portion of this large watershed. Nonetheless, it was hypothesized that a wet summer and fall in Dawson generally corresponded to a wet fall in other subwatersheds (e.g., the Steward River and the Pelly River).

4.3. Quantification of ice conditions during breakup

It is certainly not recommended nor possible to initiate the ferry season at Dawson when there is still a stationary ice cover (an intact ice cover or an ice jam) across the Yukon River at or immediately upstream of the crossing. The timing of this ice release is generally highly unpredictable, and it could trigger a bank-to-bank, intense ice run at any time. However, once the Yukon River is more than 90% open with no bank-to-bank stationary ice or ice runs along a reach extending 30 km upstream to 20 km downstream of Dawson (i.e., only stranded ice floes remain visible in secondary channels and on gravel bars, Figure 4.3.1) and if there are no major ice jams between Dawson and the Sixty Mile River (60 km upstream), an ice-adapted ferry could probably begin its season. It would potentially encounter light ice runs, including ice floes that are more than one meter-thick. If the ice concentration was to rise above a specified threshold (e.g., 10%) or, more obviously, when a major ice run would travel towards the crossing, the ferry could simply temporarily halt its operation.

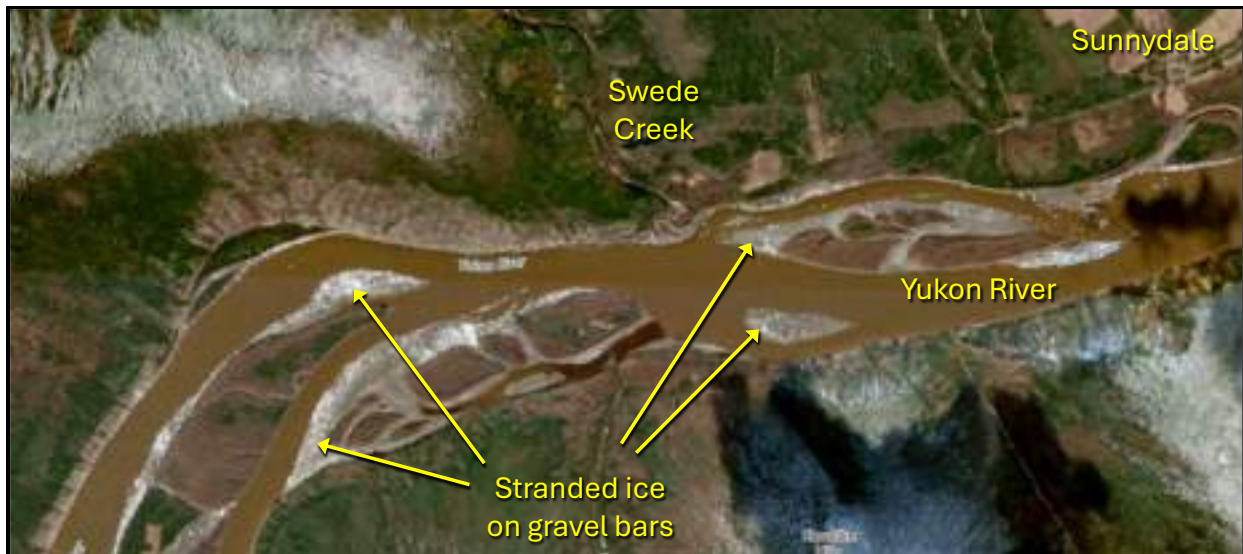


Figure 4.3.1. Segment of the Yukon River upstream of Dawson showing only stranded ice a few days after local river ice breakup. Credit: European Union – Copernicus Sentinel Data 2026.

One important question: Would it be possible to predict the timing and intensity of ice runs that occur after local river ice clearance at Dawson? The answer is no. The exact sequence of ice cover clearance in the Yukon River upstream of Dawson (even beyond the White River confluence) is different every spring, and it is extremely difficult to forecast. The frequency of Sentinel 2, RadarSat Constellation, and fixed wings surveys by the Government of Yukon, Department of Environment, although occurring on a sub-daily basis, could likely not inform the development of a model that would predict the timing and intensity of breakup ice runs (or the timing of an ice jam release), and

observations would not be frequent enough to provide reliable information in real-time. A degree-day of thaw-type of indicator would certainly not be useful here. Therefore, in the presence of a large ice jam less than 60 km upstream of Dawson, the (even an ice-adapted) ferry should remain at its overwinter site on the dike. Figure 3.2.2 presented the situation of a post-local-ice-clearance ice run that was preceded by a surge, whose amplitude eventually reached 2 m. That bank-to-bank, multi-hour ice run would have threatened any boat or large vessel.

In the case of ice jams located more than 60 km upstream of Dawson (and an open channel between the ice jam and at least 20 km below Dawson), its release would also generate an ice run and surge. However, this ice run would likely be preceded (by an hour or so) by a notable, observable rise in water levels, and the ice concentration would only increase progressively at the ferry crossing. An assessment of ice conditions that may momentarily interrupt ferry operations could easily be obtained in real-time (e.g., via a camera) from the Midnight Dome, Sunnydale, or the ferry itself. The pilot would have enough time to complete one or two crossings before the ice run concentration rises above 10% of the channel surface near the ferry path. Even dispersed ice runs originating from the Klondike River could be observed in advance. This information, combined with the use of a breakup model (e.g., Turcotte et al., 2024), could reasonably translate into a gain in the ferry season in April or May, as presented in the next section.

5. Results

This section summarizes the results of the historical assessment (2016-2025), the hindcast period (2005-2015), and the hypothetical future period (2030-2060). For the freeze-up period, the model described in Section 4.2 is used to evaluate when an ice-adapted ferry would need to be removed from the Yukon River before the formation of a full ice cover. For the spring breakup period, a quick year-by-year assessment, based on Section 4.3, is conducted for the period 2010-2025 to identify the earliest date of operation for an ice-adapted ferry.

Before presenting the project’s results, Table 5.1 shows the freeze-up model calibration and testing statistics. It is normal for errors in the model to occur for several reasons, including difficulty predicting where the first ice congestion occurs and whether it will release in the following hours or days. Therefore, the model was calibrated on the conservative side, tolerating more false positives (model over-predicts ice run intensity) than false negatives (model under-predicts) from the perspective of ice-adapted ferry operations that should not occur during intense ice runs or once the ice cover is complete. It is important for the model not to be over-calibrated for a specific data set (e.g., 2021-2025) so that it remains reasonably accurate when simulating freeze-up sequences for other years. The Yukon River has a personality that cannot be fully captured numerically, even by the most complex models. The results of the testing phase may seem relatively inaccurate, but among the identified inaccuracies (e.g., 9% false negatives), none posed a real concern.

Table 5.1. Summary of the freeze-up model calibration and test

	False negatives (ice run intensity under-estimated)	False positives (ice-run intensity over-estimated)	Model accuracy (correct classification of conditions 0, 1, 2, 3, and 4)
Calibration (2021-2025)	0%	4%	88%
Test (2016-2020)	9%	13%	56%

5.1. Historical freeze-up conditions (2005-2025)

The first analysis consists of evaluating the number of days between 1. the actual last day of ferry operations during the fall, and 2. What satellite observations and/or the model suggests in a context where the ferry would have been adapted to operate in light or moderate ice run conditions. In this case, only the documented period of 2009 to 2025 (missing 2018) can be used. Figure 5.1.1 presents the results. Readers will note that no satellite data could inform this assessment before 2015, and the dashed histogram for simulated data. Also, transient service interruptions caused by an early-season intense ice run are shown in black boxes. For those years, it would be possible to forecast improvements in ice conditions and the possibility to further extend ferry operations simply by looking at weather forecasts and using the model developed in this work (or an updated version).

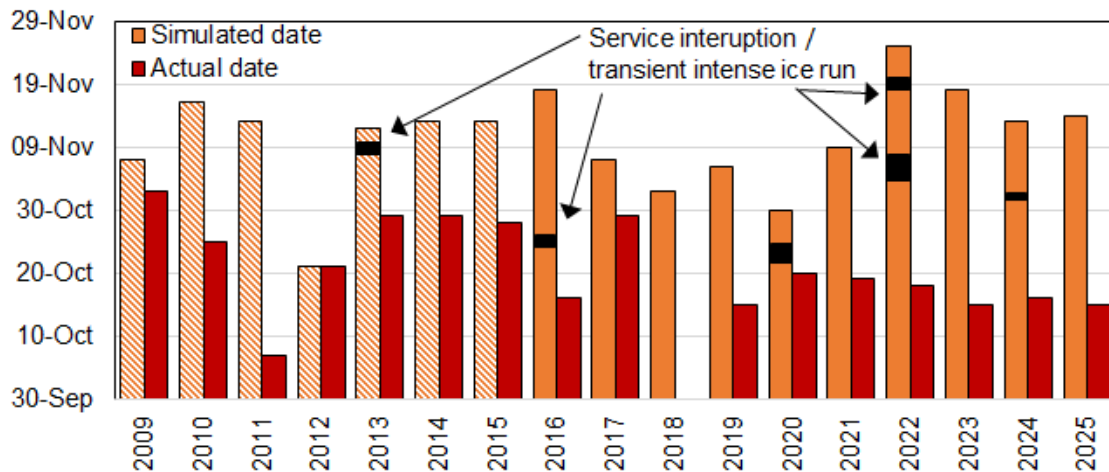


Figure 5.1.1. Histogram showing the simulated (informed or not by complementary satellite information) and actual last ferry dates at Dawson from 2009 to 2025. The simulation considers operating an ice-adapted ferry during light or moderate ice runs.

The results shown in Figure 5.1.1 suggest that the ferry season could have been extended by 20 days, on average (considering days of service interruption), between 2009 and 2025 if the George Black Ferry had been adapted to operating in partial ice conditions. Graphs in Appendix A present year-by-year simulated and observed daily ice run intensities for those years. Readers will appreciate that, in 2012, the simulated and actual last ferry dates corresponded exactly (at the beginning of a cold spell), and that no simulated date has occurred before an actual date since 2009. This should bring confidence in the model.

The second analysis compares the difference between 1. The last day of ice-adapted ferry operations, as simulated by the model, and 2. October 15, a fixed date for the last ferry crossing. This conservative last-ferry date was adopted in recent years by the Department of Highways and Public Works at the request of West Dawsonites who prefer planning certainty over a possibly extended ferry season (S. Nagano, Personal Communications, 2025). It is acknowledged that the actual historical last-ferry dates, as presented in the previous analysis differ. Figure 5.1.2. reveals that, statistically, the ferry season could have been extended by 26 days, on average (November 9), beyond the fixed date of October 15 for the historical period of 2005 to 2025 (no data in 2008). When considering possible ferry service interruptions due to transient, early-season, intense ice runs, this extension period drops to 25 days. A complete freeze-up occurs on average on November 14.

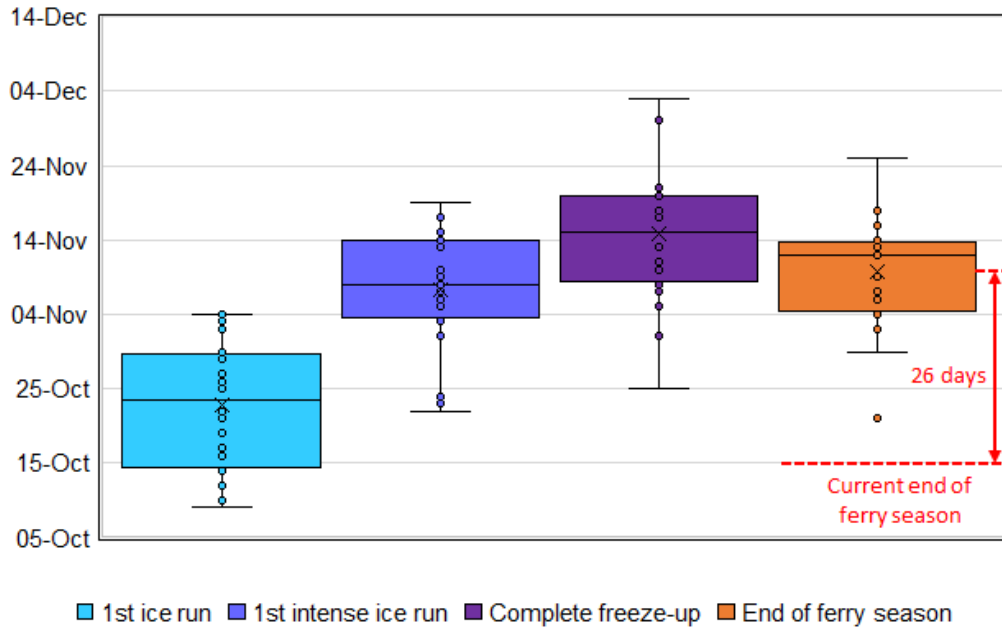


Figure 5.1.2. Statistics of the simulated results for the period of 2005 to 2025 showing the date of the first ice run (intensity 1), the first intense ice run (intensity 3), freeze-up at Dawson (level 4), and the simulated end of season for an ice-adapted ferry.

5.2. Future freeze-up conditions (2030-2060)

This section explores simulation results for future conditions, including the impact of climate change, on the freeze-up sequence of the Yukon River at Dawson. Because future last ferry dates cannot be anticipated, the analysis considers, by continuity, October 15 as a fixed last ferry date for each fall between 2030 and 2060. The results presented in Figure 5.2.1 (with detailed results in Appendix A) indicate that a future ice-adapted ferry season could be extended by 27 days on average beyond October 15, representing two additional days compared with the period 2005-2025. The average last-ferry date of November 11 (November 10 for 2030-2040 and November 12 for 2050-2060) is identified in a moderately pessimistic climate warning scenario. When including short periods of ferry interruption during early-season intense ice runs (intensity 3, followed by less-intense ice runs, 0, 1, or 2), this period is reduced, on average, by 1 day.

Readers will note that these results seem to correspond to a limited amount of warming over the next 30+ years. The same dataset suggests that the average annual temperature near Dawson will warm to -2.6°C in the future (2030-2060), compared with the historical (1960-2025) reference of -4.3°C . However, it is important to note that temperatures in the shoulder seasons are significantly influenced by the sun angle and day length; it is not surprising that river ice freeze-up dates would not change significantly in the future. Generally, the simulated future weather and its processed results by the freeze-up model described in Figure 4.2.1 appear realistic.

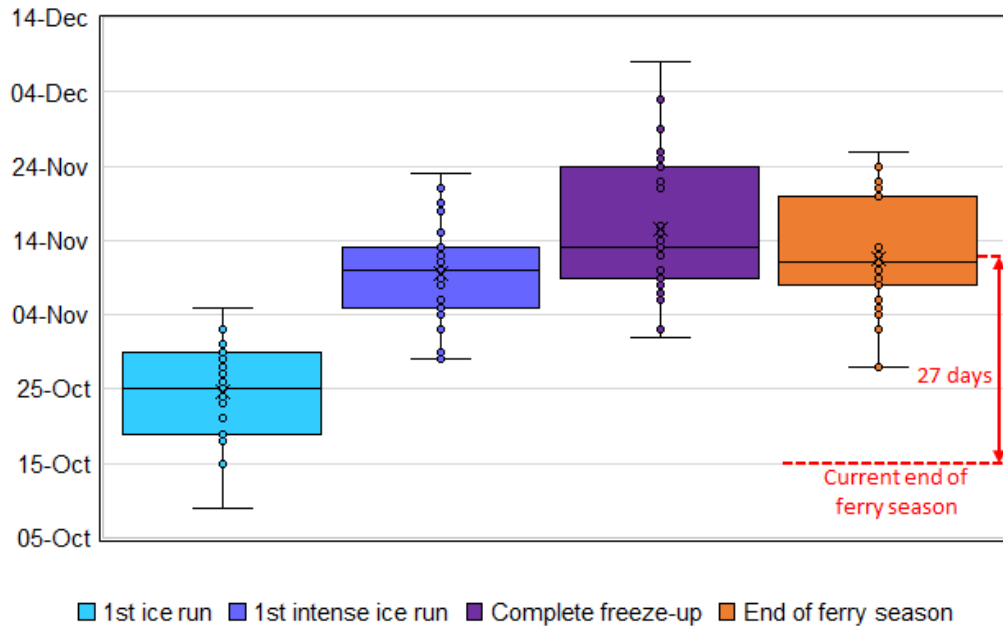


Figure 5.2.1. Statistics of the simulated results for the period of 2030 to 2060 (SSP3-7.0 climate scenario) showing the date of the first ice run (intensity 1), the first intense ice run (intensity 3), freeze-up at Dawson (level 4), and the simulated end of season for an ice-adapted ferry.

5.3. Historical breakup conditions

Various sources were used to identify ice-clearing dates in a reach extending from 60 km upstream of Dawson to 20 km downstream of Dawson. These sources include Satellite imagery, stage records provided by the Water Survey of Canada for station 09EB001 located at Dawson, ground photos, and breakup reports prepared by the Government of Yukon, Department of Environment. Actual dates of ferry season initiation were also shared by the Department of Highways and Public Works for this project, covering the period 2010 to 2025 (2 of the 3 gaps were filled using satellite imagery). The results presented in Figure 5.3.1 suggest that a ferry that would be adapted to operate in light breakup ice runs (less than 10% ice concentration) could initiate its season, on average, 9 days earlier than the George Black Ferry. Of course, the preparation and maintenance of the vessel prior to river ice breakup also influences the initiation of the ferry season.

Future breakup conditions cannot be known or easily simulated for reasons explained in Section 4.3. Therefore, it is not possible to use future weather to forecast breakup dates for the period 2030-2060, as was done for the freeze-up period. However, a climate change trend could be extrapolated from historical breakup dates, which have been compiled on the website yukonriverbreakup.com since 1896. The trend shown in Figure 5.3.2 indicates that breakup has occurred earlier over the past 13 decades at an average rate of 0.6 days per decade. Therefore, it can be approximated that the ferry season could be advanced by 1 to 4 days, on average, between 2030 and 2060. This, of course, will depend on several factors and will vary annually by +/- 30 days, centered around May 1 to May 4.

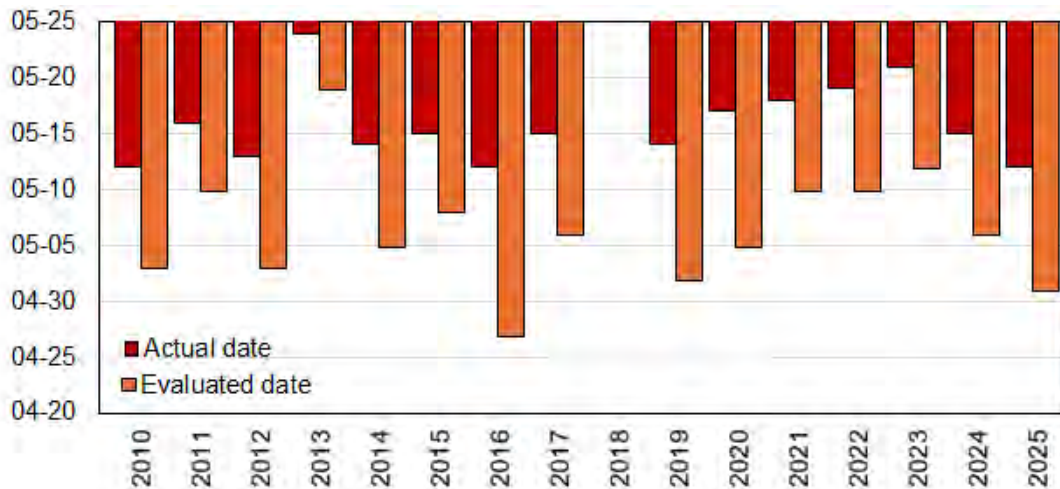


Figure 5.3.1. Histogram showing the optimal (evaluated) and actual first ferry dates at Dawson from 2010 to 2025. The evaluated date occurs after local ice clearance and last significant ice run.

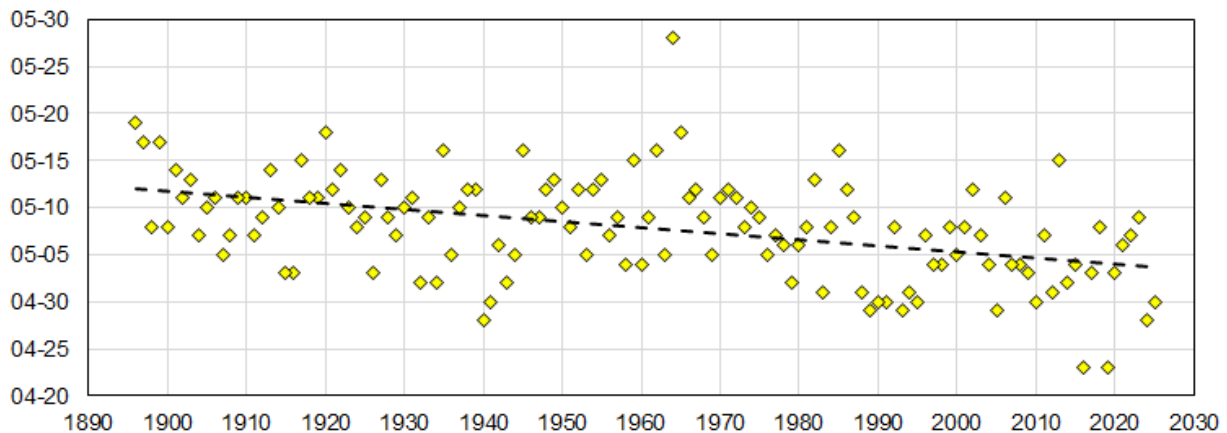


Figure 5.3.2. Historical breakup dates at Dawson (first sustained ice movement, which may be different from ice-clearance dates) from 1896 to 2025, including a linear trend.

6. Project summary and recommendations

In the Northwest Territories (NWT), the last day of the ferry season is communicated about 3 days in advance to locals, travellers and freight to plan for transportation interruption (Government of Northwest Territories, Personal Communication 2026). That date is established by considering water-level variations (caused by freeze-up), ice conditions, and weather forecasts, and it does not seem that any model informs end-of-season decisions (some sites have a more predictable freeze-up sequence than others). Based on the information shared by the Gov. of NWT, no NWT ferry operates during heavy slush runs or in the presence of large ice pans (Section 3.3). In the Spring, the Gov. of NWT waits until all upstream ice jams and covers have cleared before initiating the sailing season.

This project has investigated the intensity of freeze-up ice runs in the Yukon River for historical (2005-2025) and future (2030-2060) periods by using a simple numerical model that relies on readily available input data (weather and water levels). The timing of the last significant spring breakup ice

run was also investigated using various data sources for the historical period (2010-2025), and projections (2025+) were briefly explored by extrapolating current trends.

Based on the information that was accessed or provided for this project, here are some important results:

- **Current conditions:** The last George Black Ferry crossing in the fall has been set for October 15 in recent years. The first day of the ferry season in the spring is, on average, May 15 (based on 2010-2025 data). This means that the current season lasts, on average, 153 days.
- **New ice-adapted ferry and optimal operations:** Technically, if:
 - The ferry was adapted to operate in cold conditions and moderate slush runs in the fall (up to 70% slush concentration with no or little ice consolidation) as well as in light ice runs in the spring (less than 10% ice floe concentration),
 - It was possible to manage border ice in the fall, shear walls (beached ice floes) in the spring, as well as the formation of ice on the ferry's hull and frost on its deck,
 - A freeze-up model of the Yukon River at Dawson as used to inform decisions regarding the last ferry date at least 3 days in advance,
 - The existing river ice breakup model (Turcotte et al., 2024) was used to identify a possible range of breakup dates at Dawson in order to inform pre-season ferry preparation, The ferry season could be extended to an average of 188 days (an additional 26 days in the fall and 9 days in the spring). Moreover, the ice-adapted ferry could support the formation of a complete ice cover at Dawson by breaching a freeze-up jam that would have formed upstream of Dawson. This, however, assumes that the Federal regulation would support such cold condition ferry operations.
- **New standard ferry and optimal operations:** If the George Black Ferry was replaced by an equivalent vessel that would operate in similar light ice conditions, but with optimal planning and maintenance (and the use of freeze-up and breakup models to forecast ice conditions), and if the fixed date of October 15 was left aside, the ferry season could last, on average, 172 days, from May 10 (estimated last residual breakup ice run) to October 22 (first moderate ice run).

Regardless of the preferred ferry replacement option, based on a preliminary assessment, climate change would likely extend the ferry season by 3 days in the fall and 4 days in the spring, for a total of 7 days by 2050-2060.

The author of this work is not an expert in ferry operations in cold regions, nor is he a professional engineer specialized in the design of vessels and ships in fluvial environments. Therefore, it is **recommended** that:

- The scientific content of this work be shared with engineers who will be responsible for further evaluating design options and flexibility in the navigation regulation to replace the George Black Ferry.
- The Department of HPW consider the creation of a multidisciplinary team composed of local knowledge holders, river engineers, river ice specialists, and ship designers.

This would also be important when considering a cabled ferry option and the design and construction of permanent ferry ramps.

Future steps of this work could include:

- **Updated freeze-up model** (Regardless of the design of the next ferry, and if the fixed last ferry date of October 15 is rejected): Improve the freeze-up model developed in this project, so that it provides an accurate 3-day forecast and a moderately accurate 7-day forecast of ice conditions in the Yukon River at Dawson to inform ferry operations.
- **Monitoring** (If the ice-adapted ferry is considered to replace to George Black Ferry): Continue to monitor supercooling conditions and ice conditions during freeze-up in 2026 and 2027 to inform freeze-up model calibration (Note that a high-resolution temperature sensor was deployed in the Yukon River in October 2025. The sensor, with the data it contains, will be retrieved in the summer of 2026). Monitoring the water temperature from the ferry's deck during the last weeks of the season could also be considered. In addition, further documenting the consolidation state of the freeze-up ice run and the thickness, as well as size of drifting ice floes, would also be important for informing the design of an ice-adapted ferry.
- **Climate change** (Regardless of the design of the next ferry, and if the fixed last ferry date of October 15 was rejected): Consider using different climate scenarios (various carbon emission intensities) to explore how a warming spring and fall could affect the duration of the ferry season. Readers will have noted that the climate change assessment presented in this report is relatively simple.

Acknowledgement

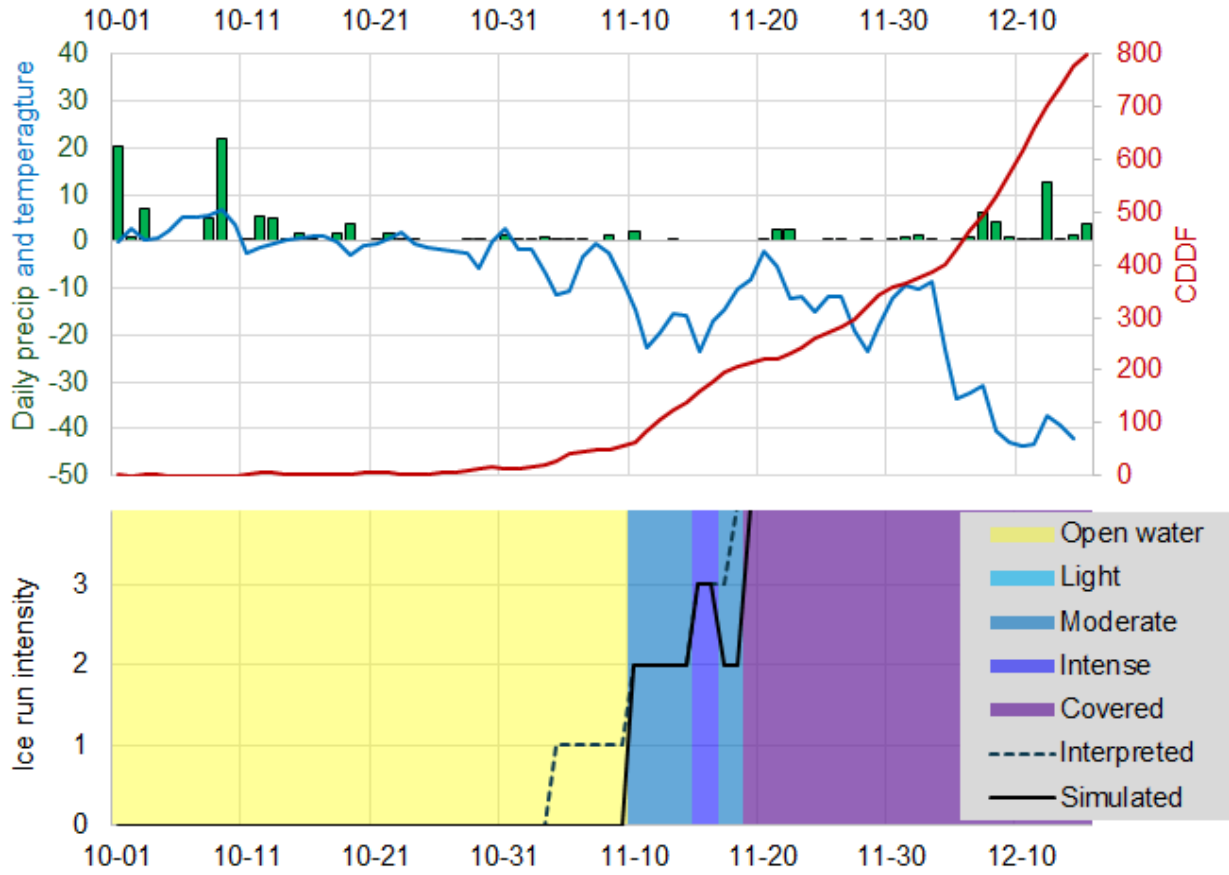
The author is grateful for the opportunity to work on this project with the Government of Yukon, Department of Highways and Public Works – Transportation Engineering Branch. Simon Nagano, a Dawson resident and owner of Klondike H₂O, provided pictures and comments for this report. The Government of Northwest Territories provided answers to questions related to ferry operations in the Mackenzie River watershed. Julien Schroder, from the Government of Yukon, produced and shared future (2030-2060) weather conditions for this project. YukonU Research Center colleagues Avery Zammit and Brian Horton provided a review of the report. YukonU Research Center colleague Stephanie Saal performed an assessment of Sentinel 1 satellite data. Sentinel 1 and Sentinel 2 imagery was obtained online and is provided by the European Space Agency. Historical weather and hydrological data were obtained from Environment and Climate Change Canada.

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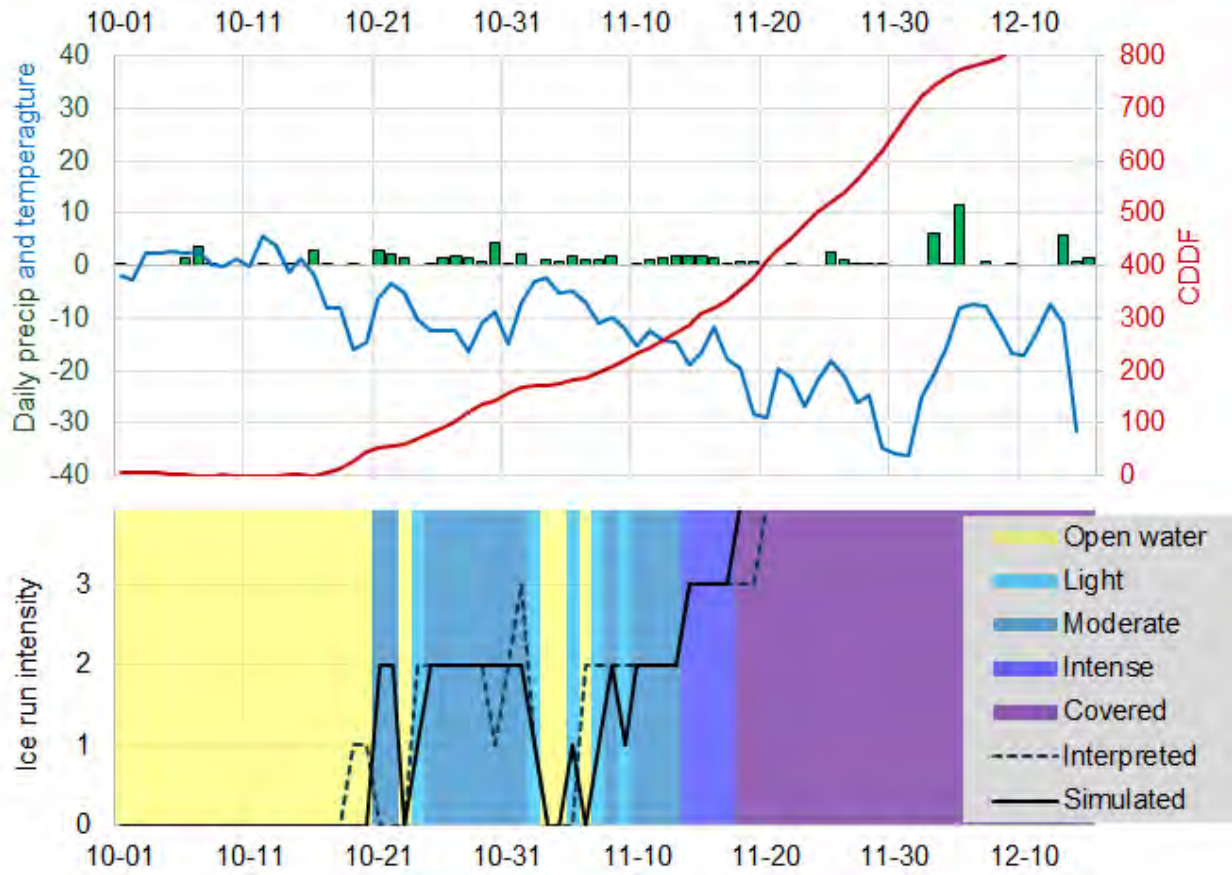
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Appendix A - Historical freeze-up conditions

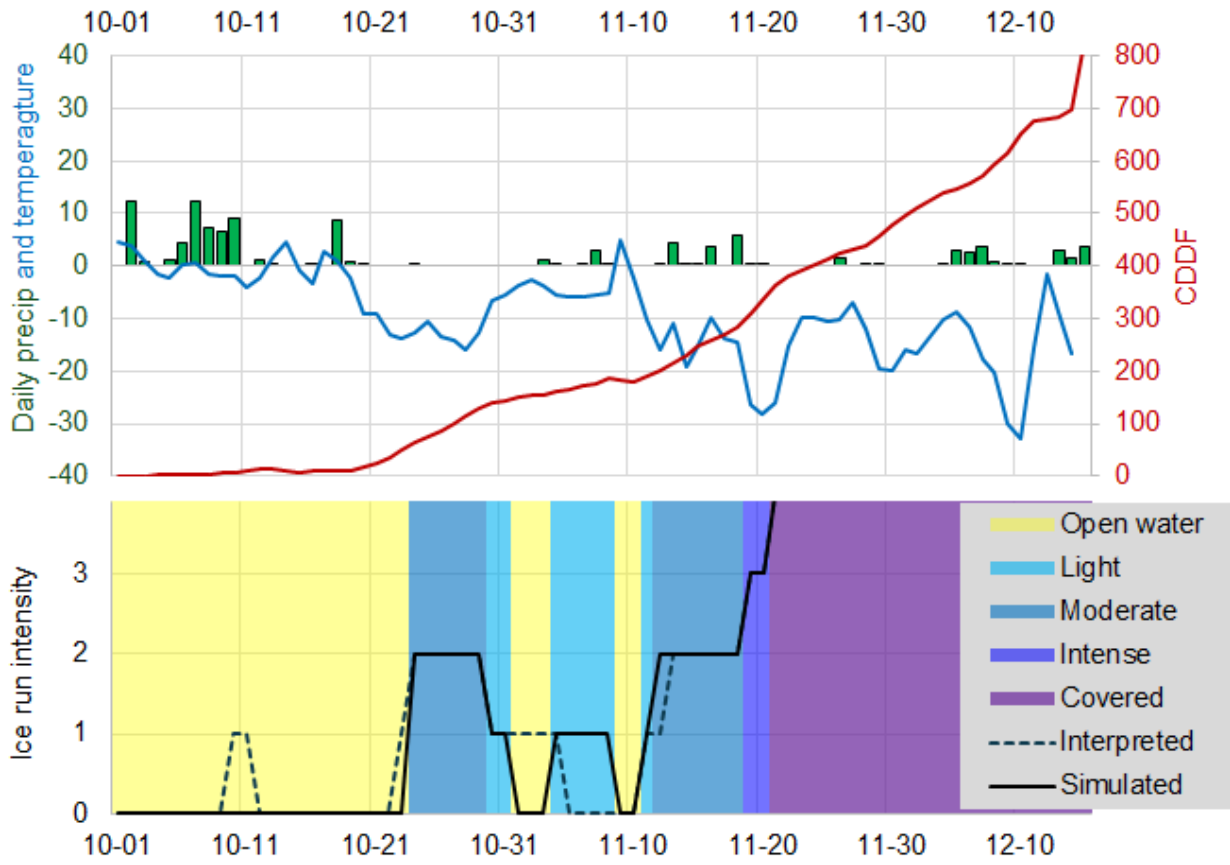
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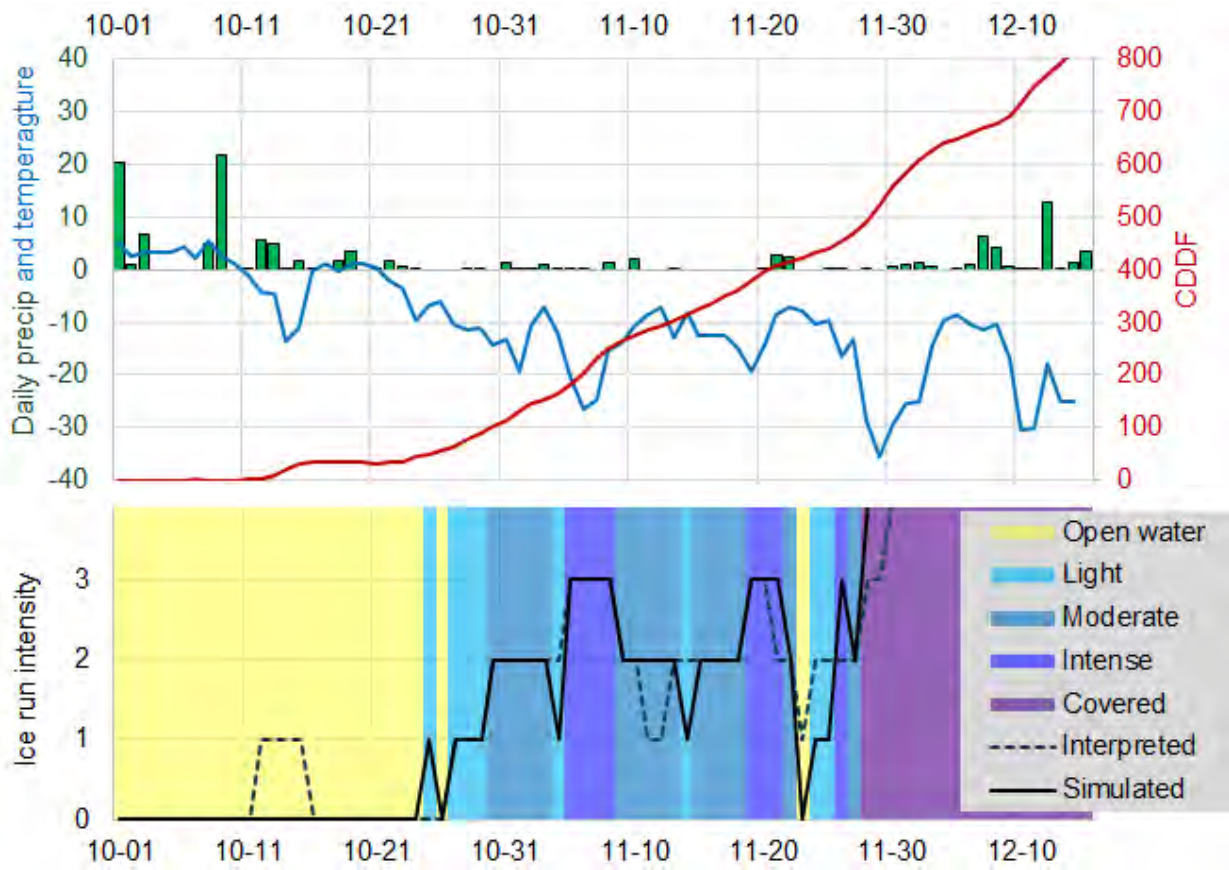
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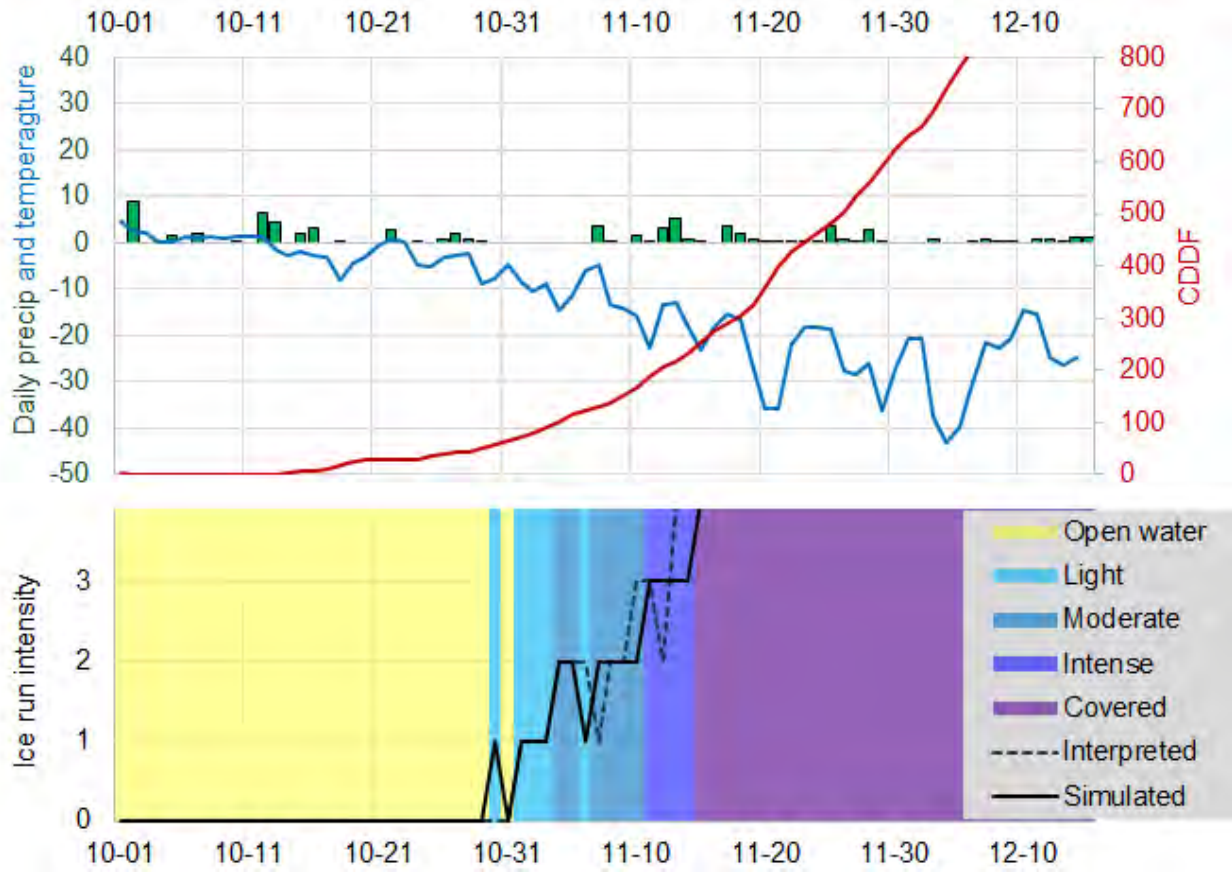
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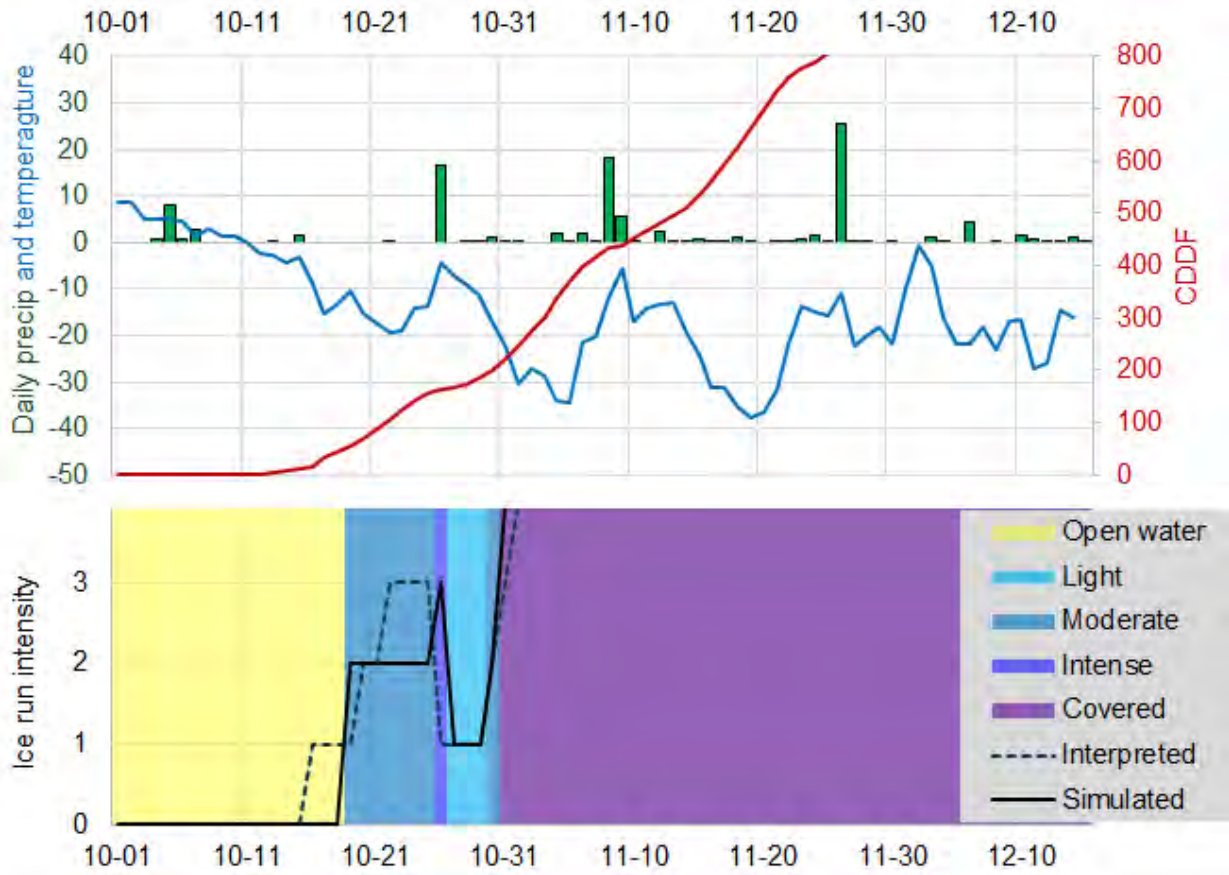
2022



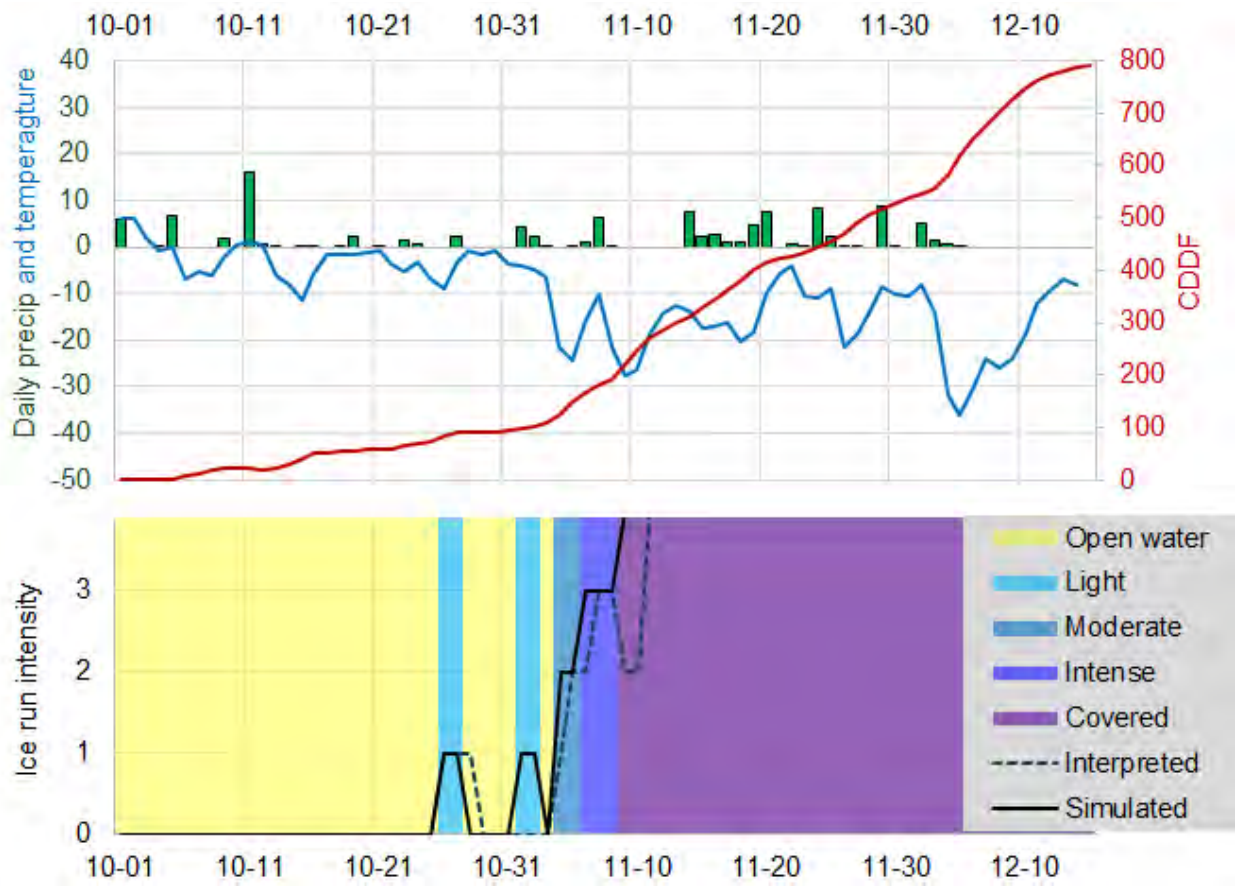
2021



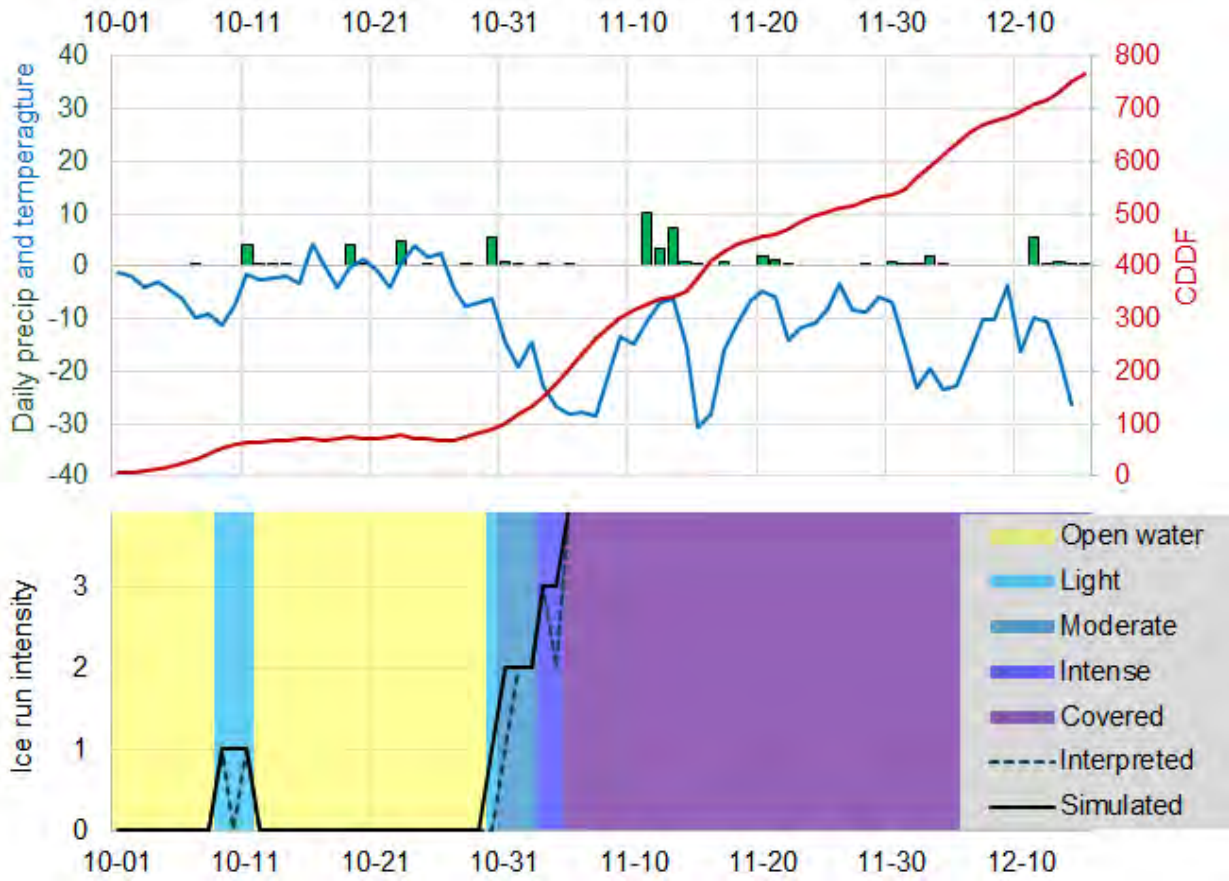
2020



2019



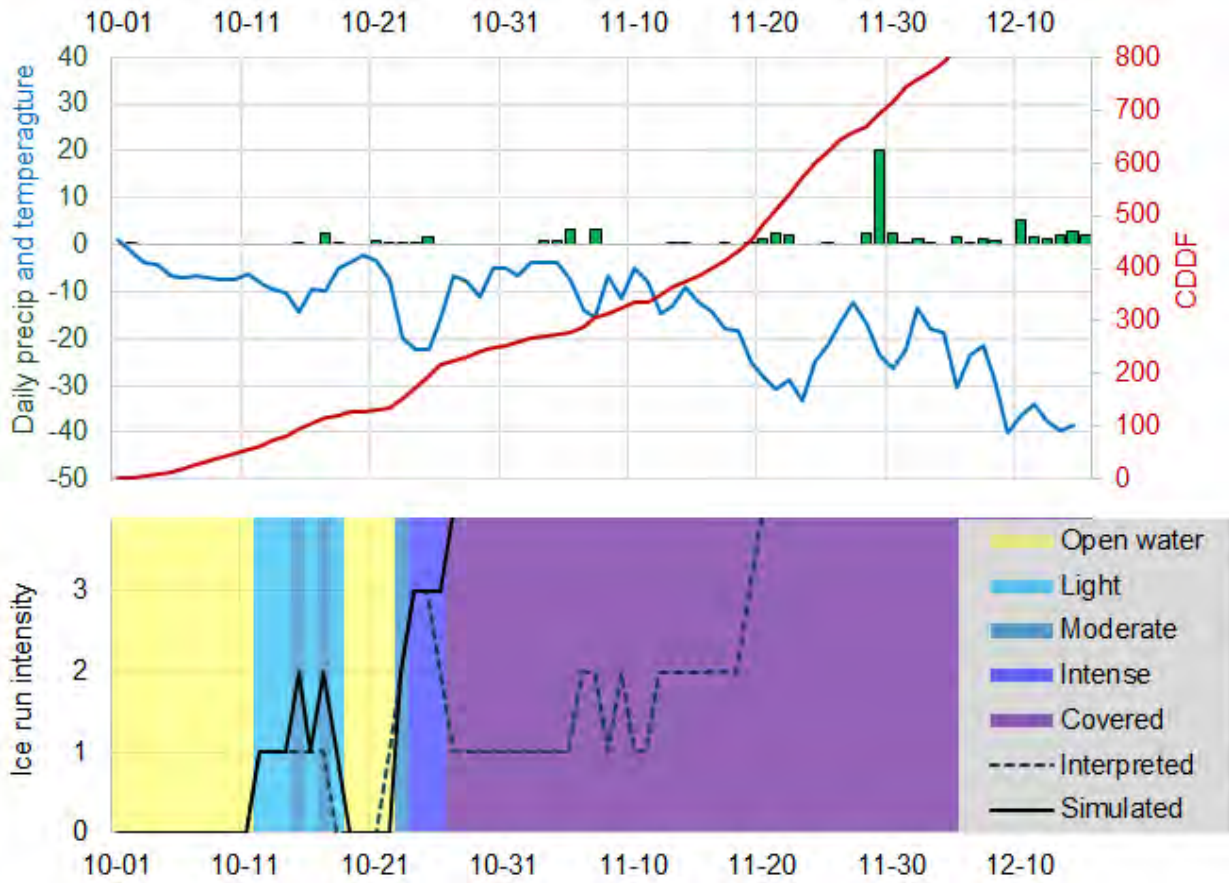
2018



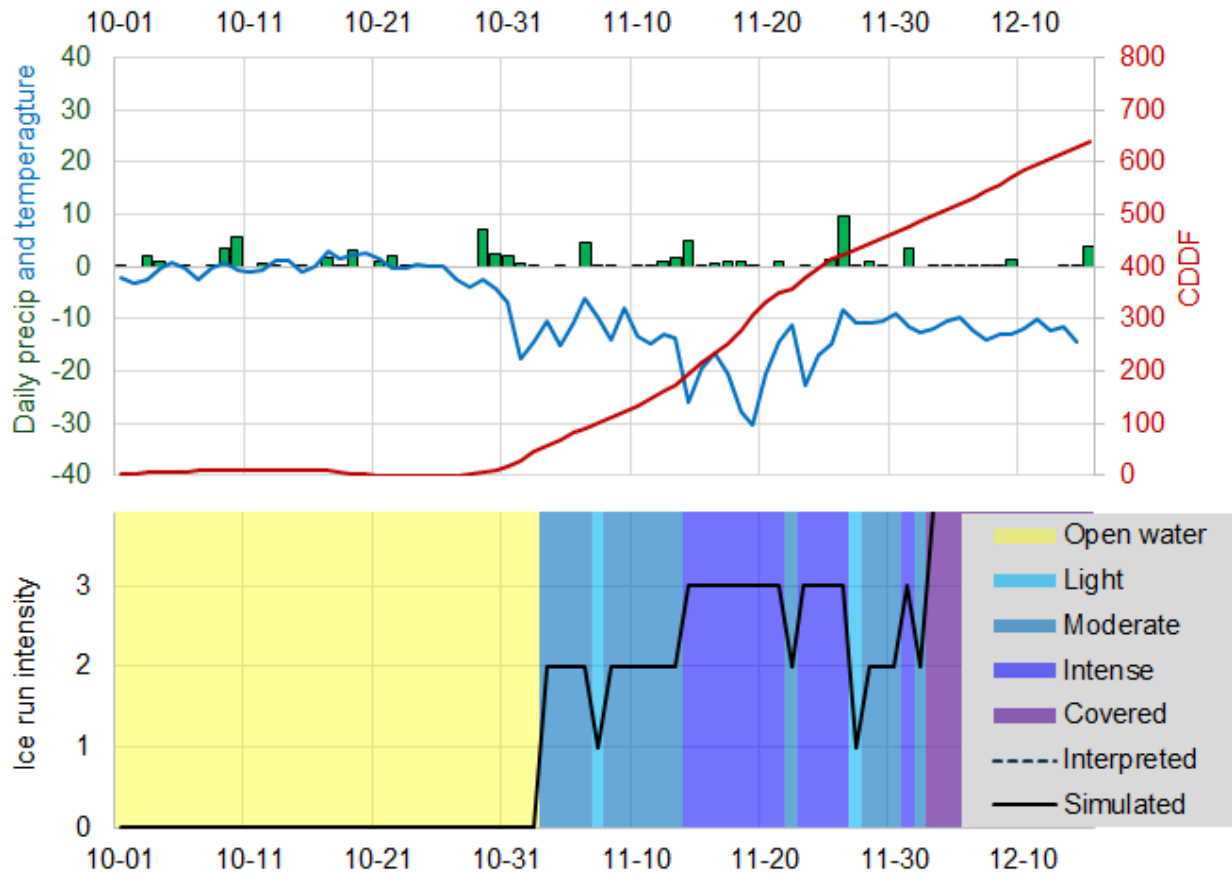
2017



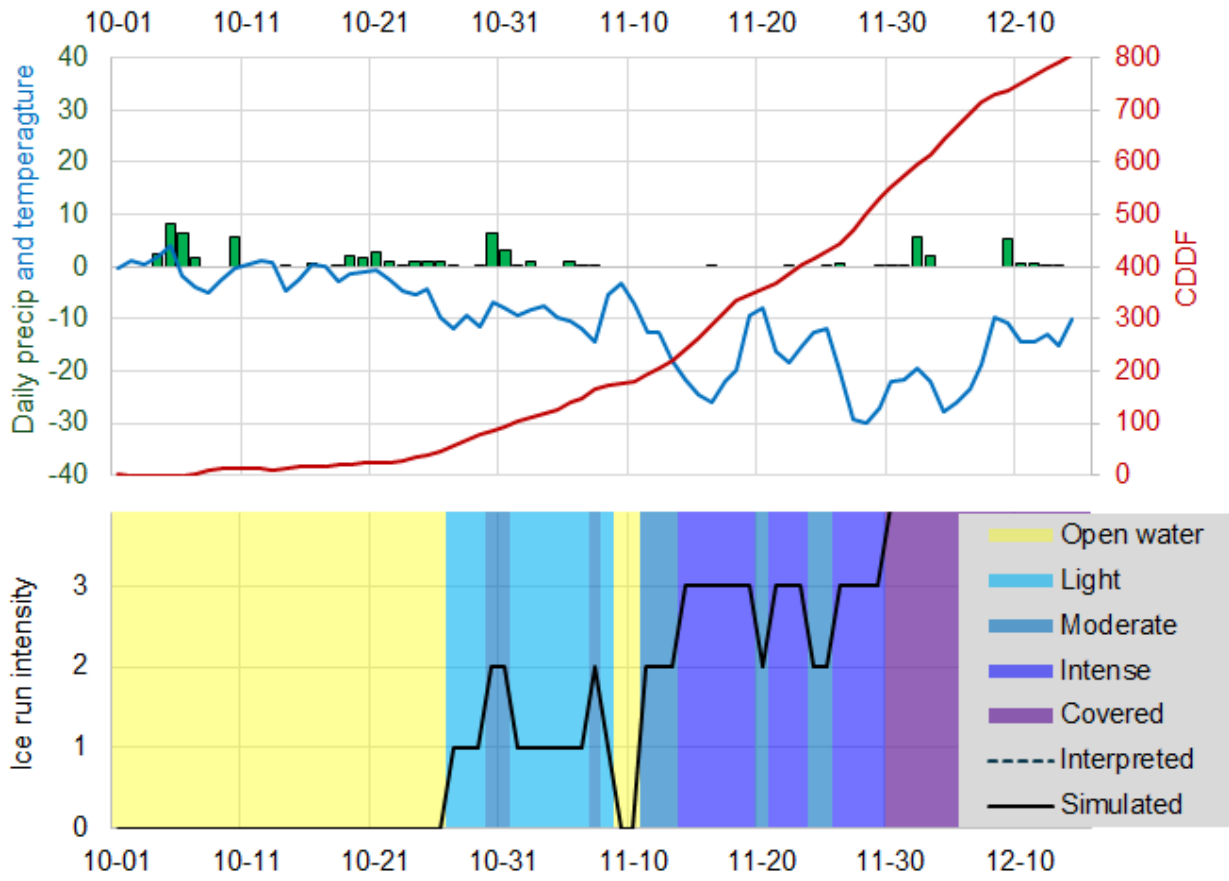
2016



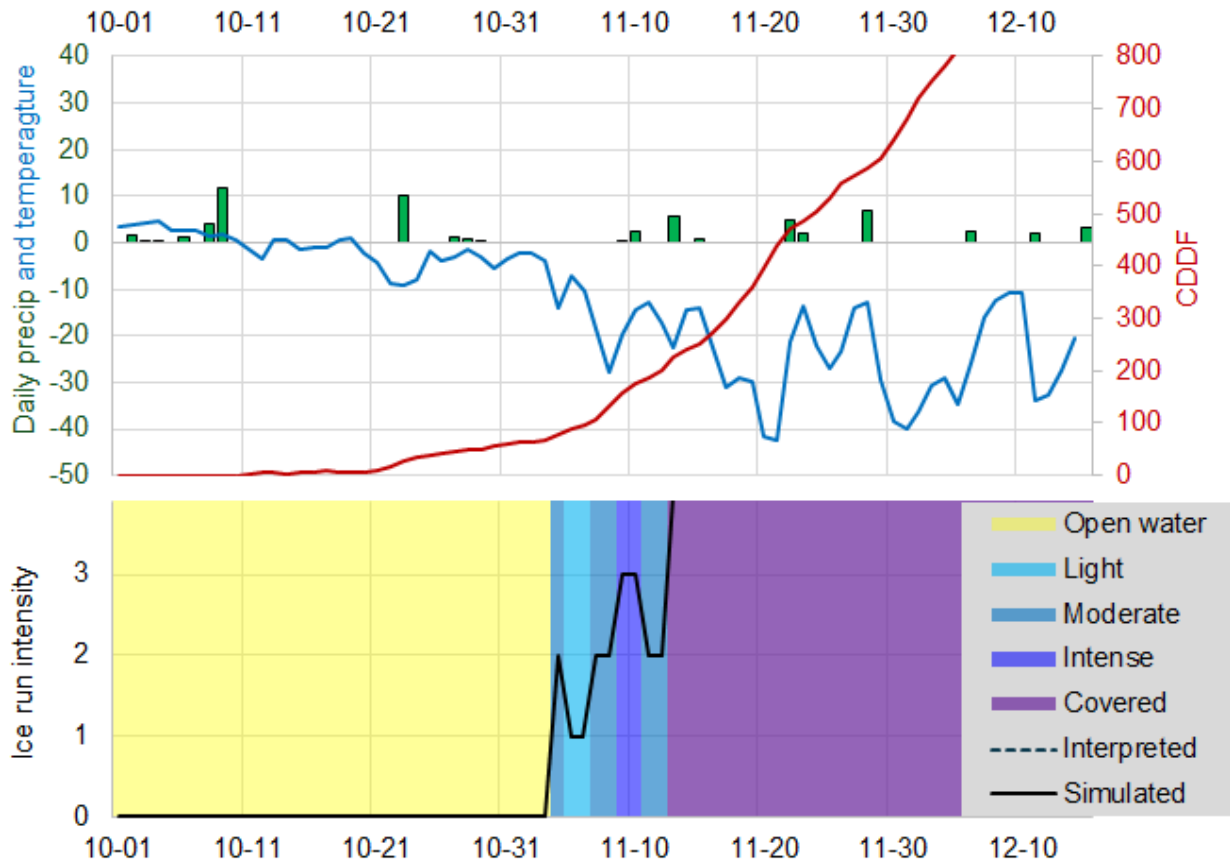
2015 (no satellite data)



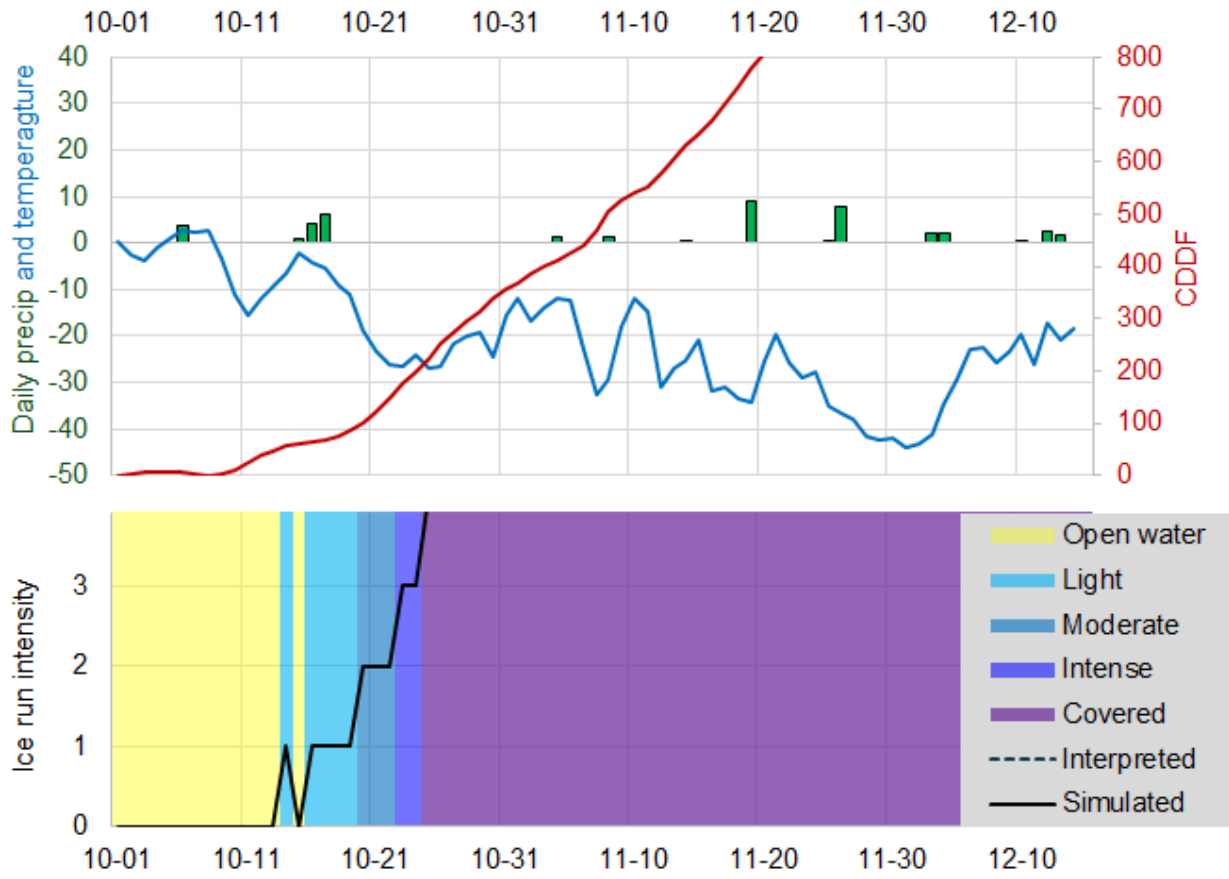
2014 (no satellite data)



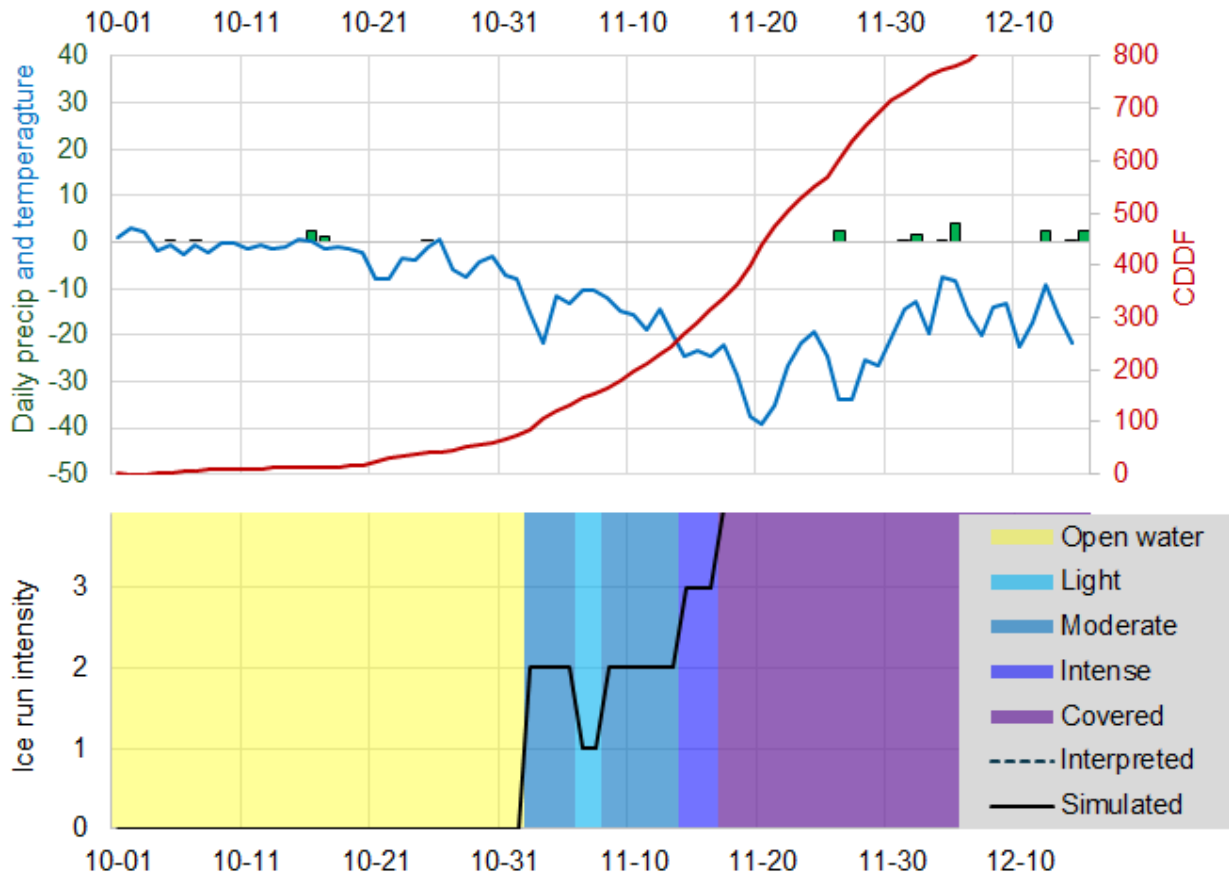
2013 (no satellite data)



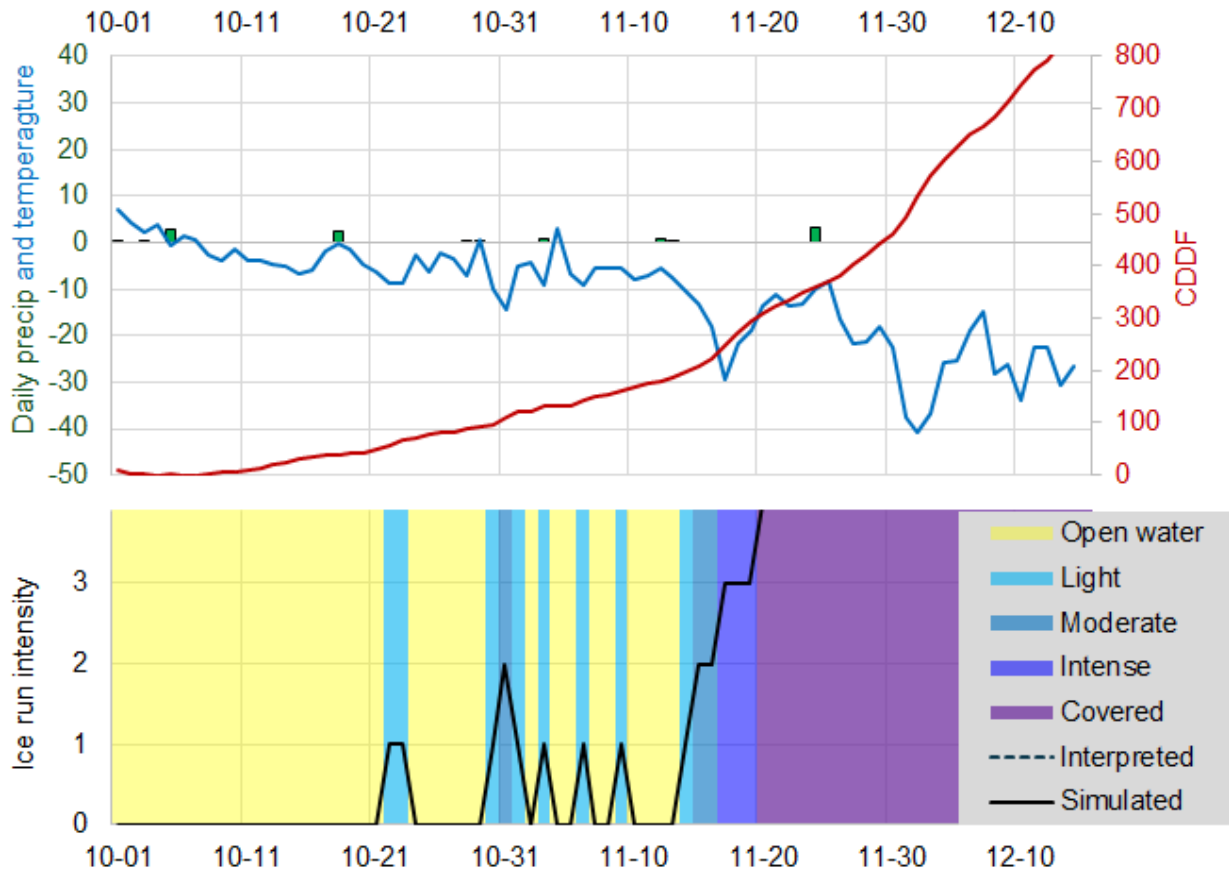
2012 (no satellite data)



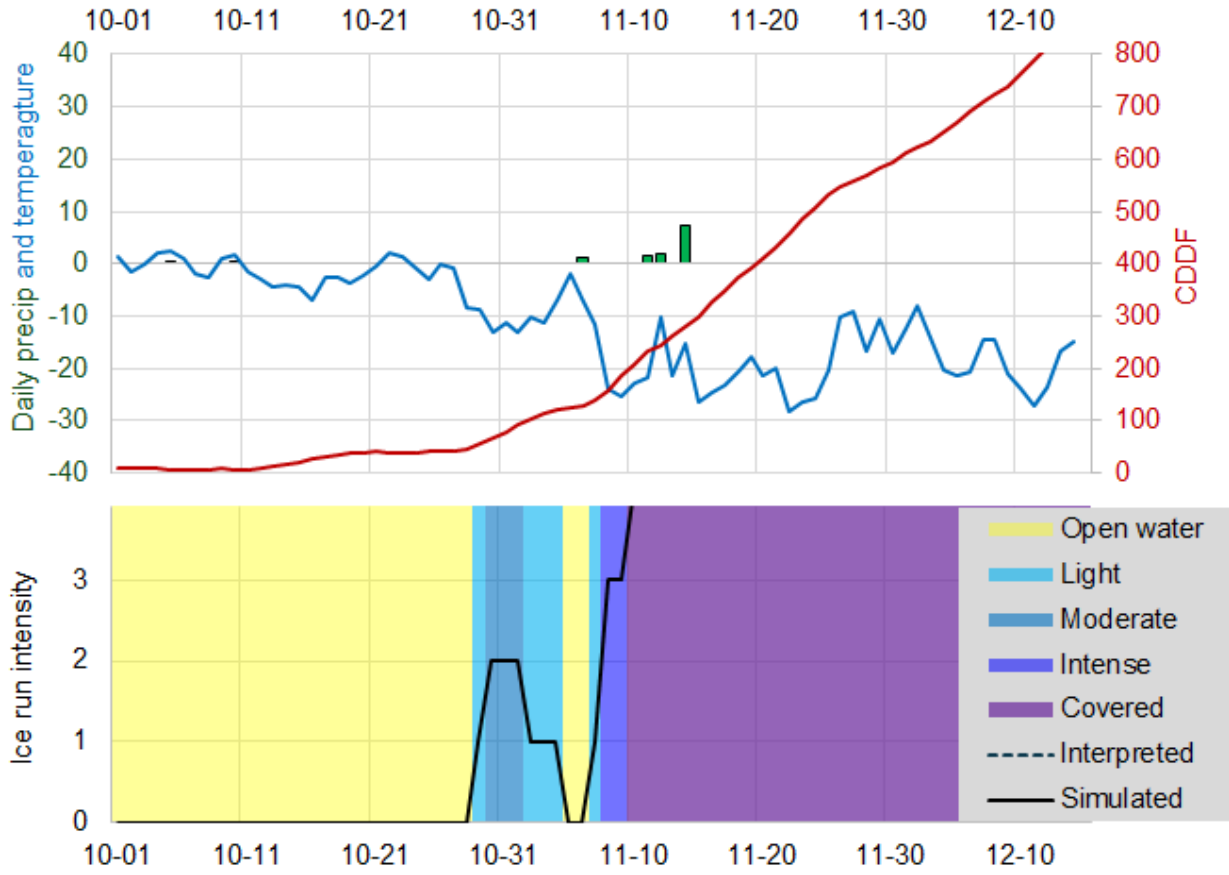
2011 (no satellite data)



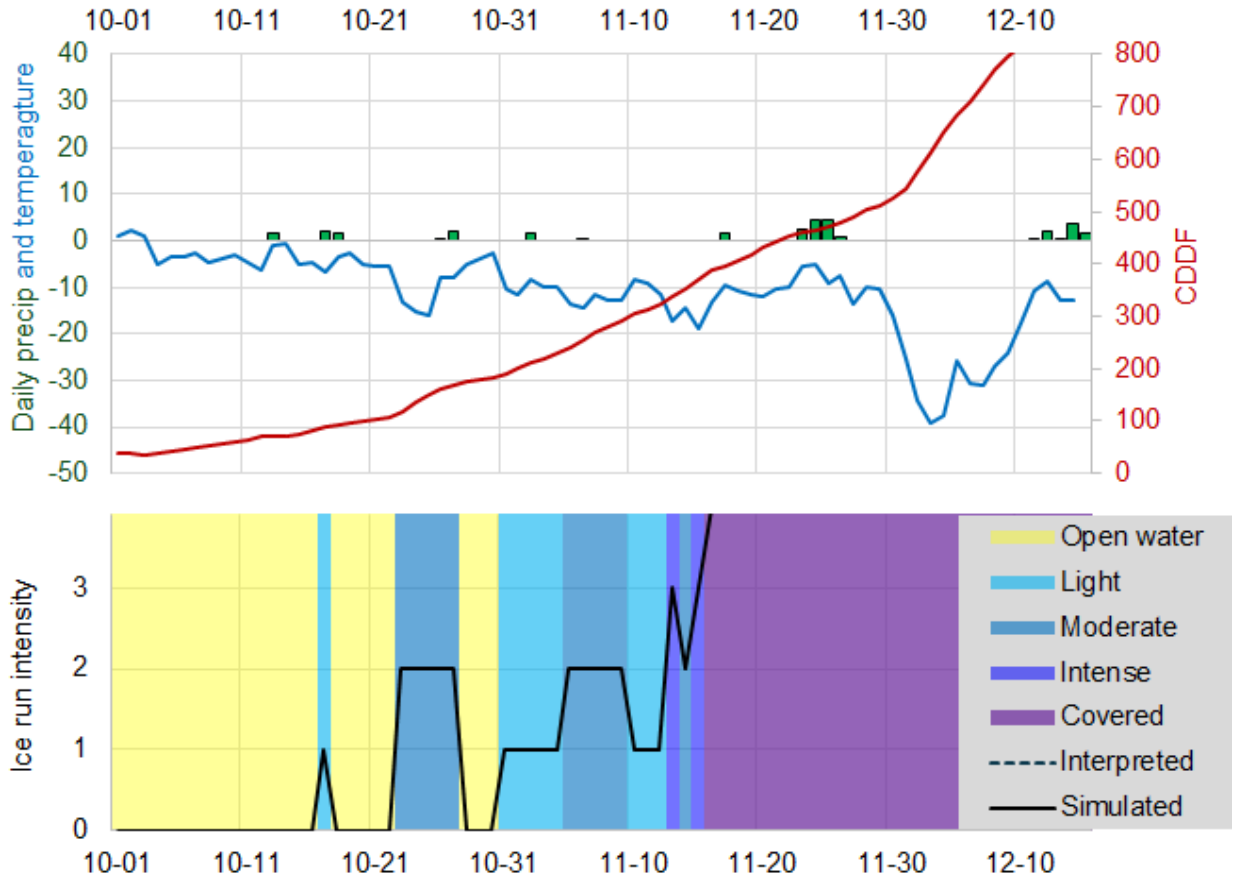
2010 (no satellite data)



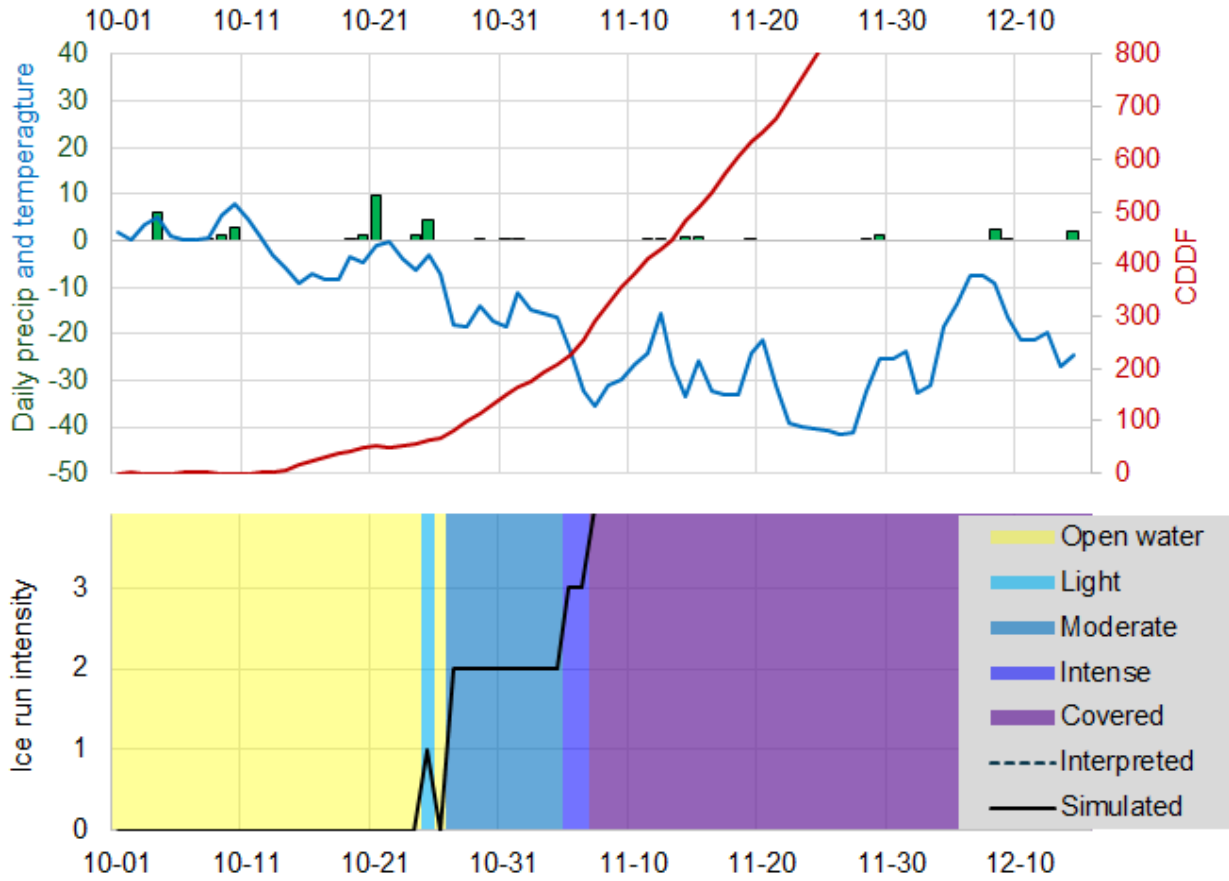
2009 (no satellite data)



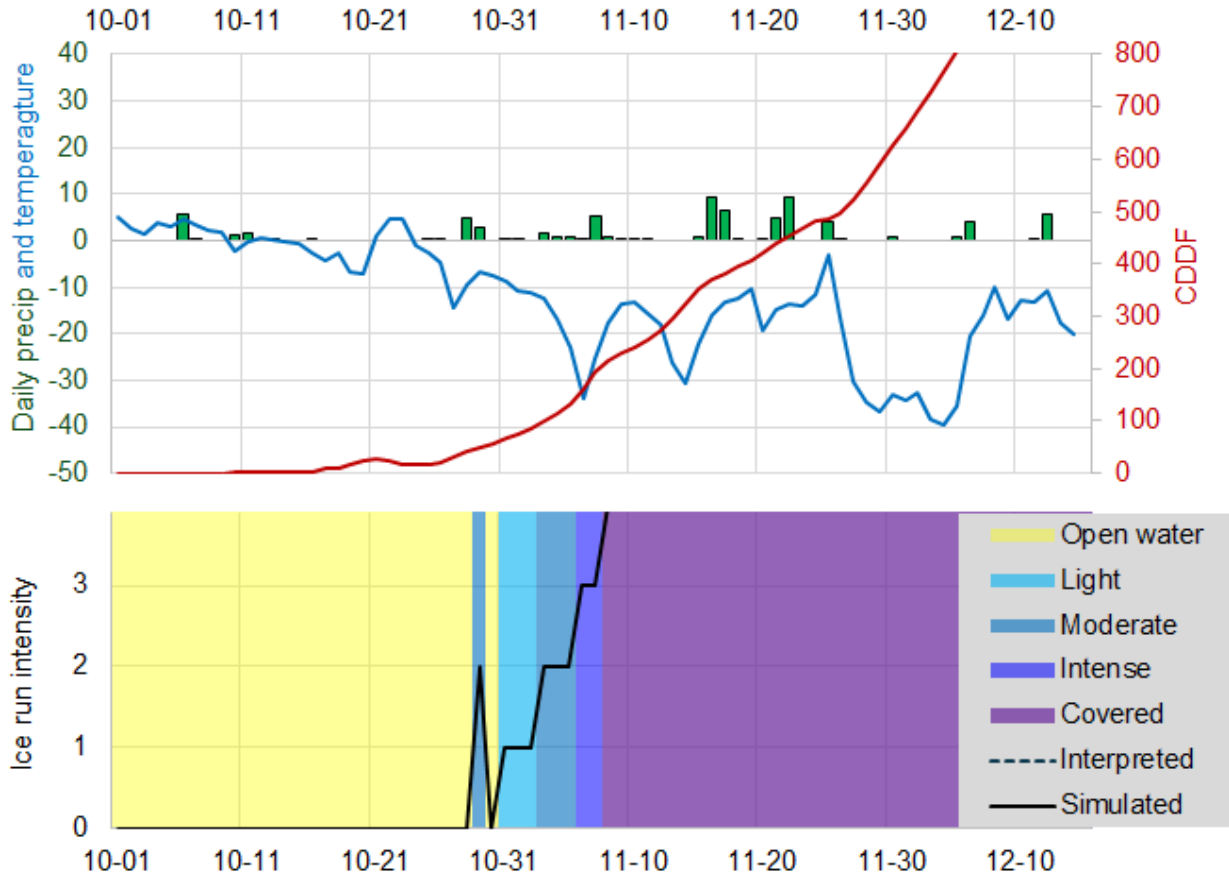
2007 (no satellite data)



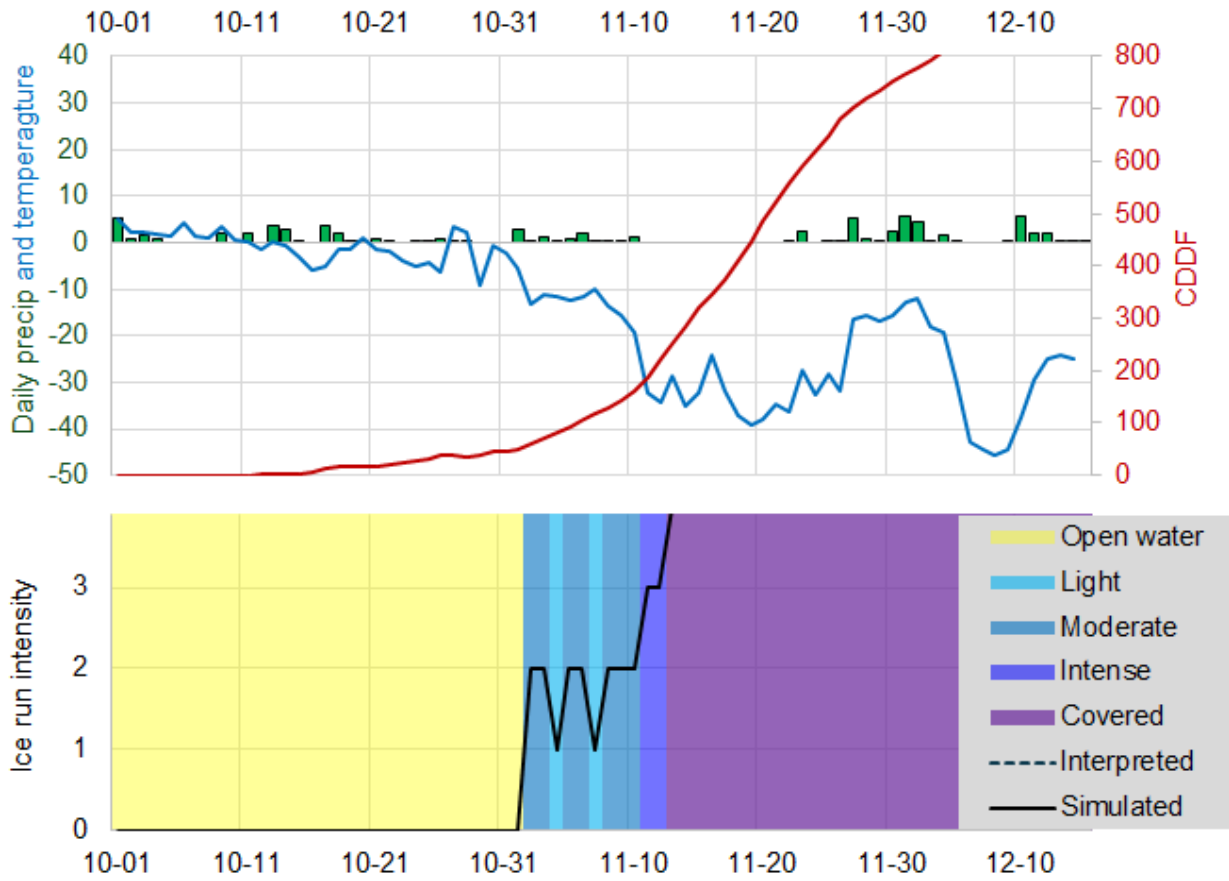
2006 (no satellite data)



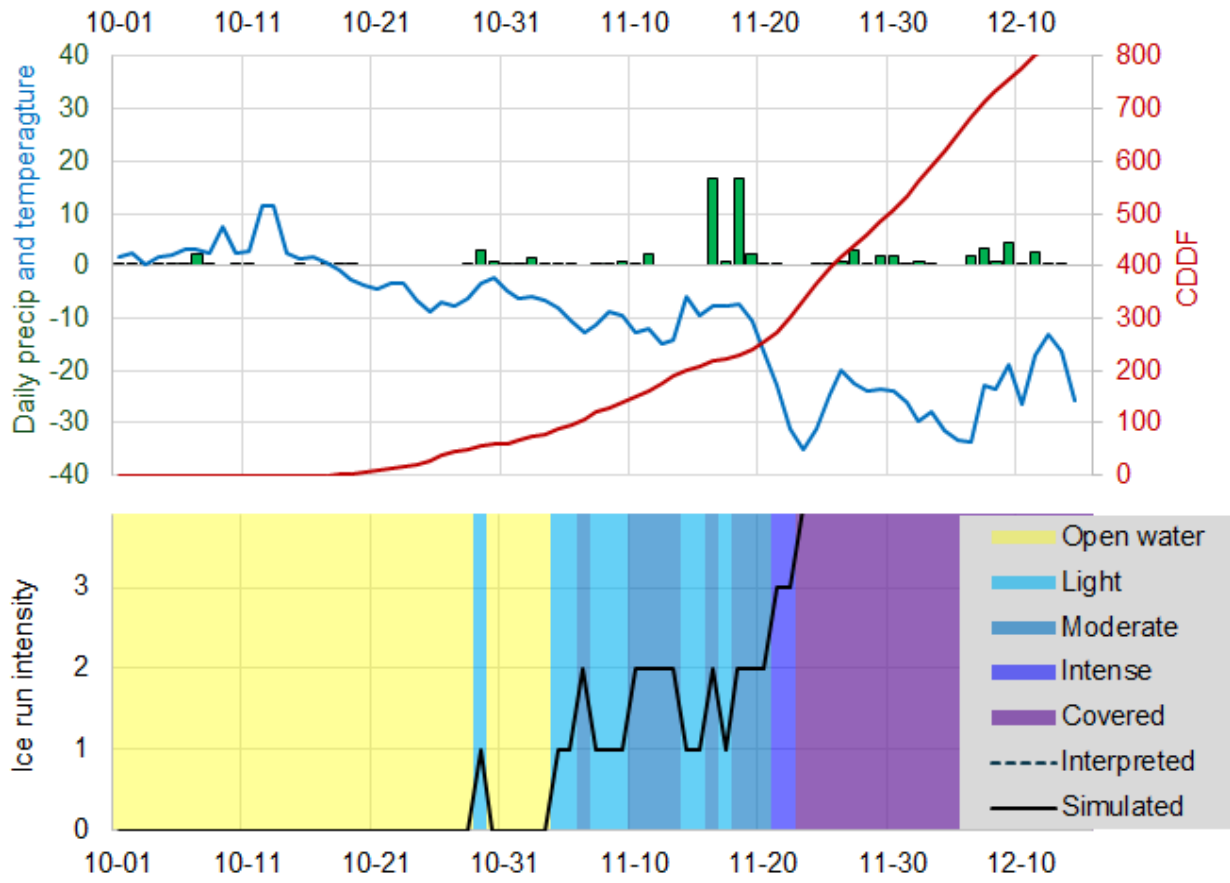
2005 (no satellite data)



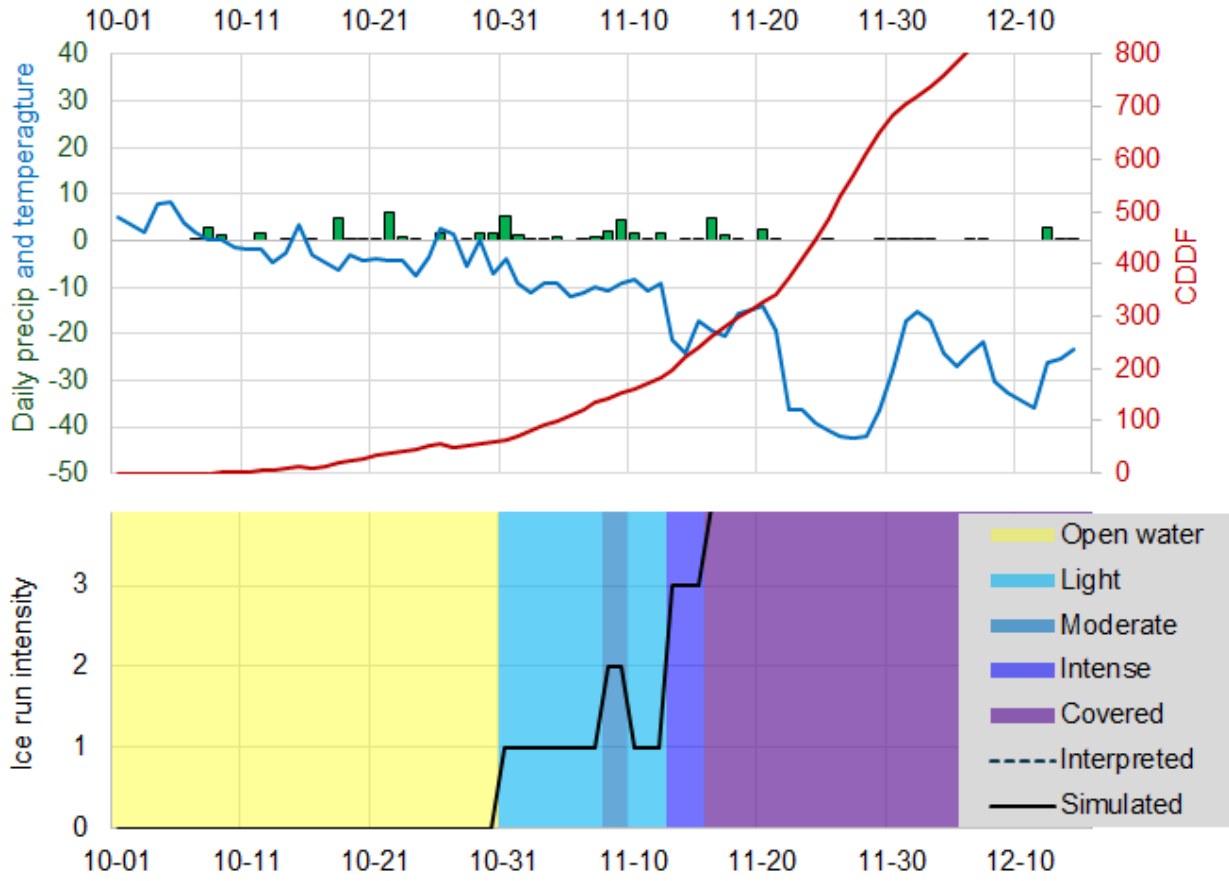
2030 (projections)



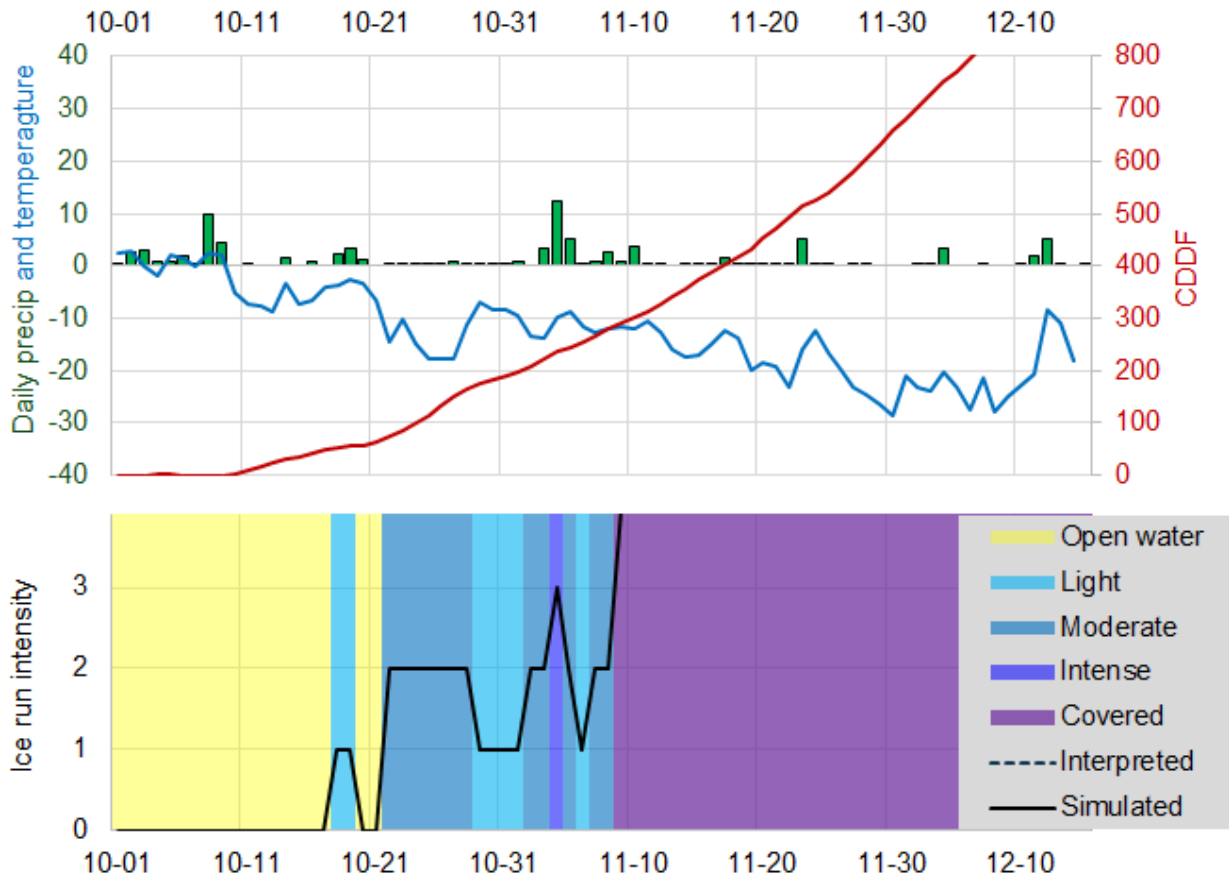
2031 (projections)



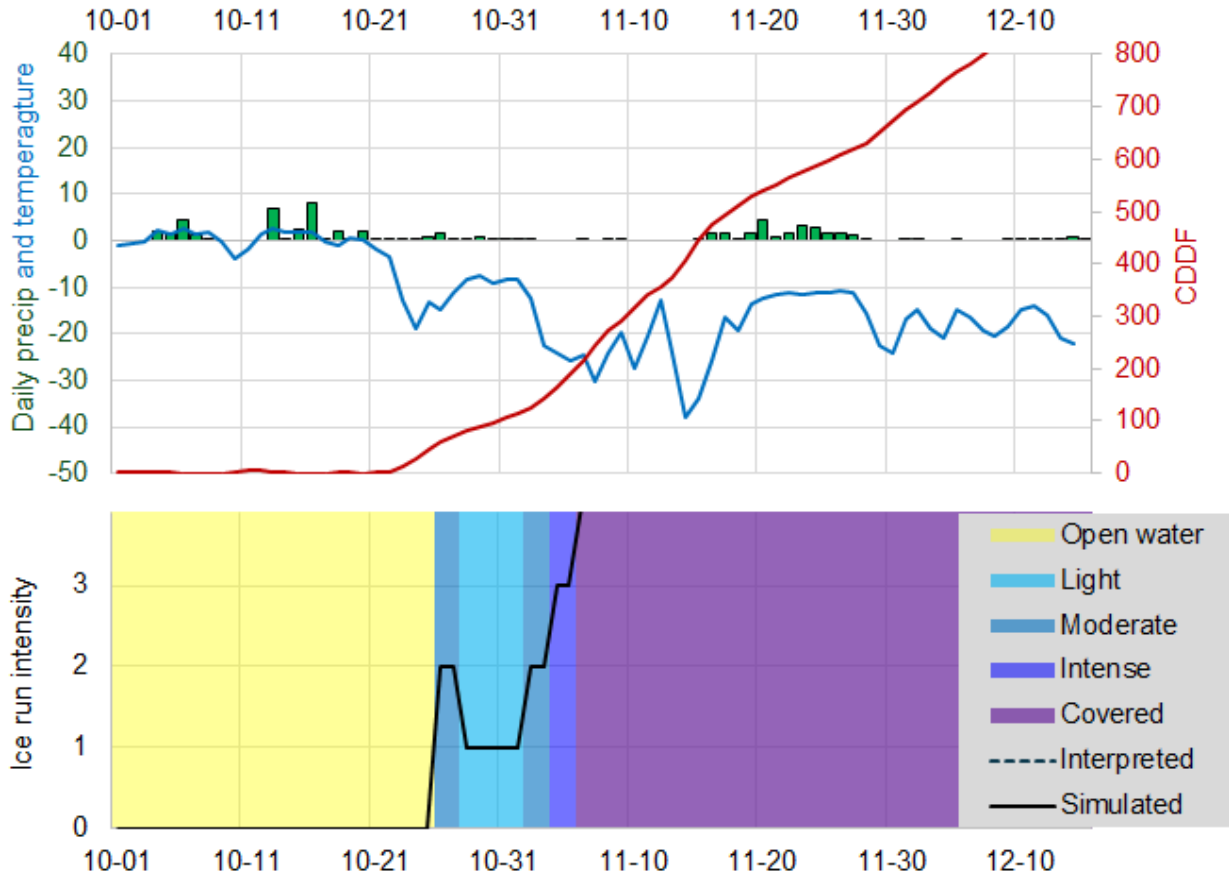
2032 (projections)



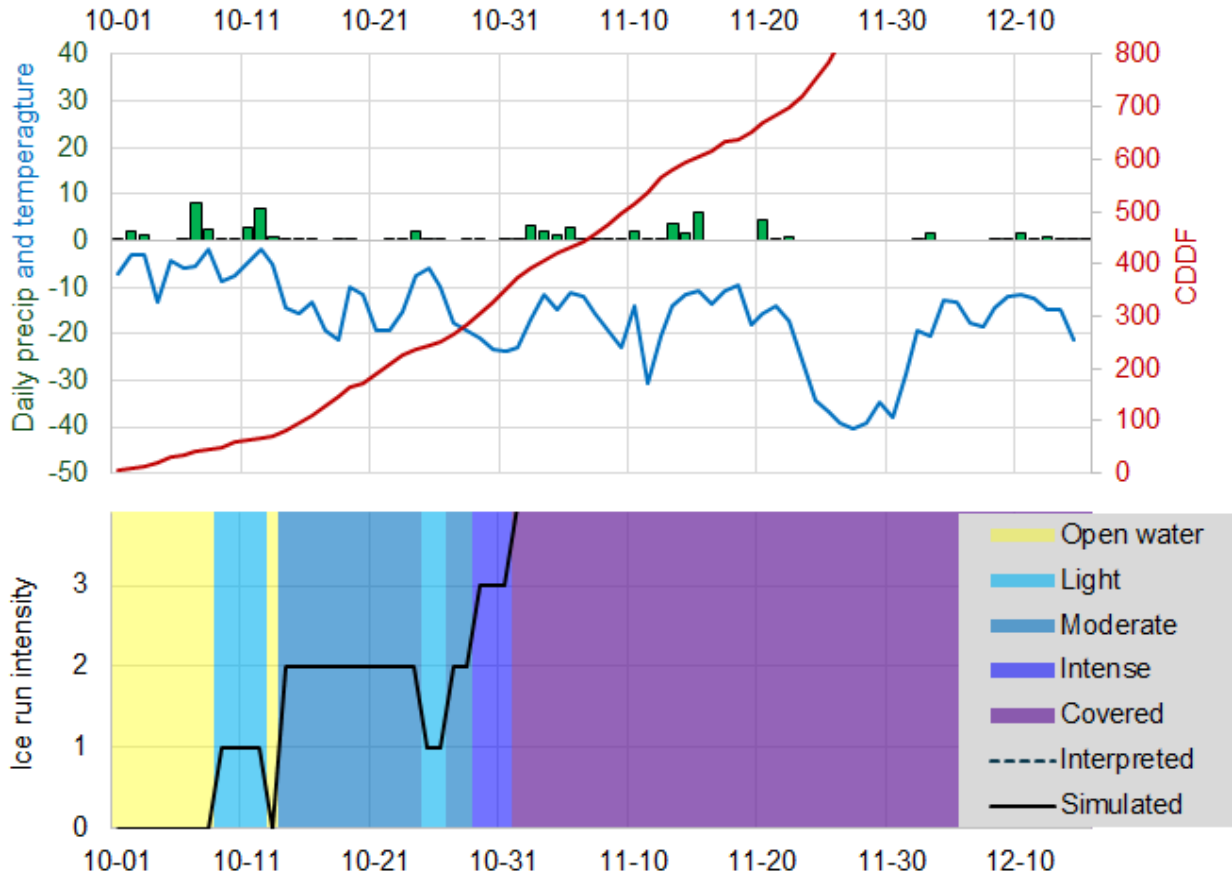
2033 (projections)



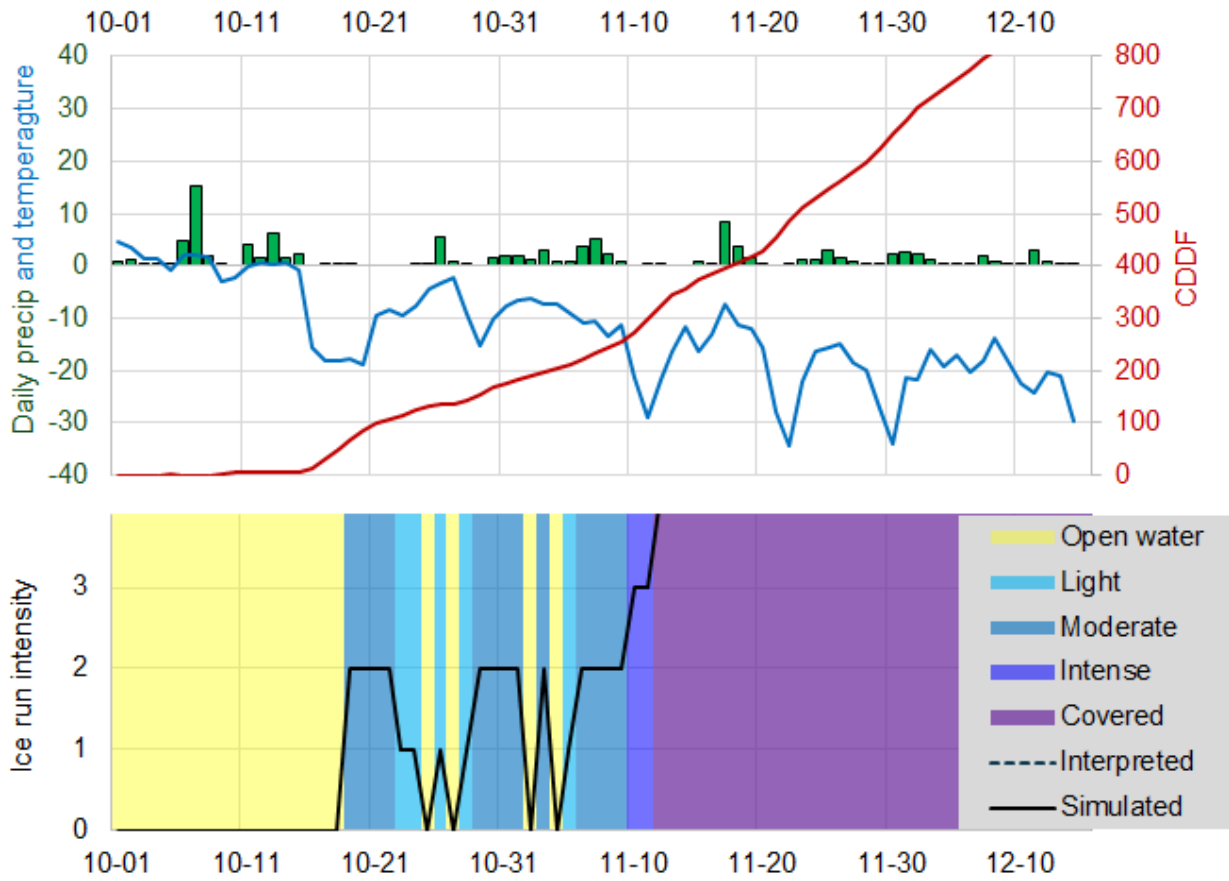
2034 (projections)



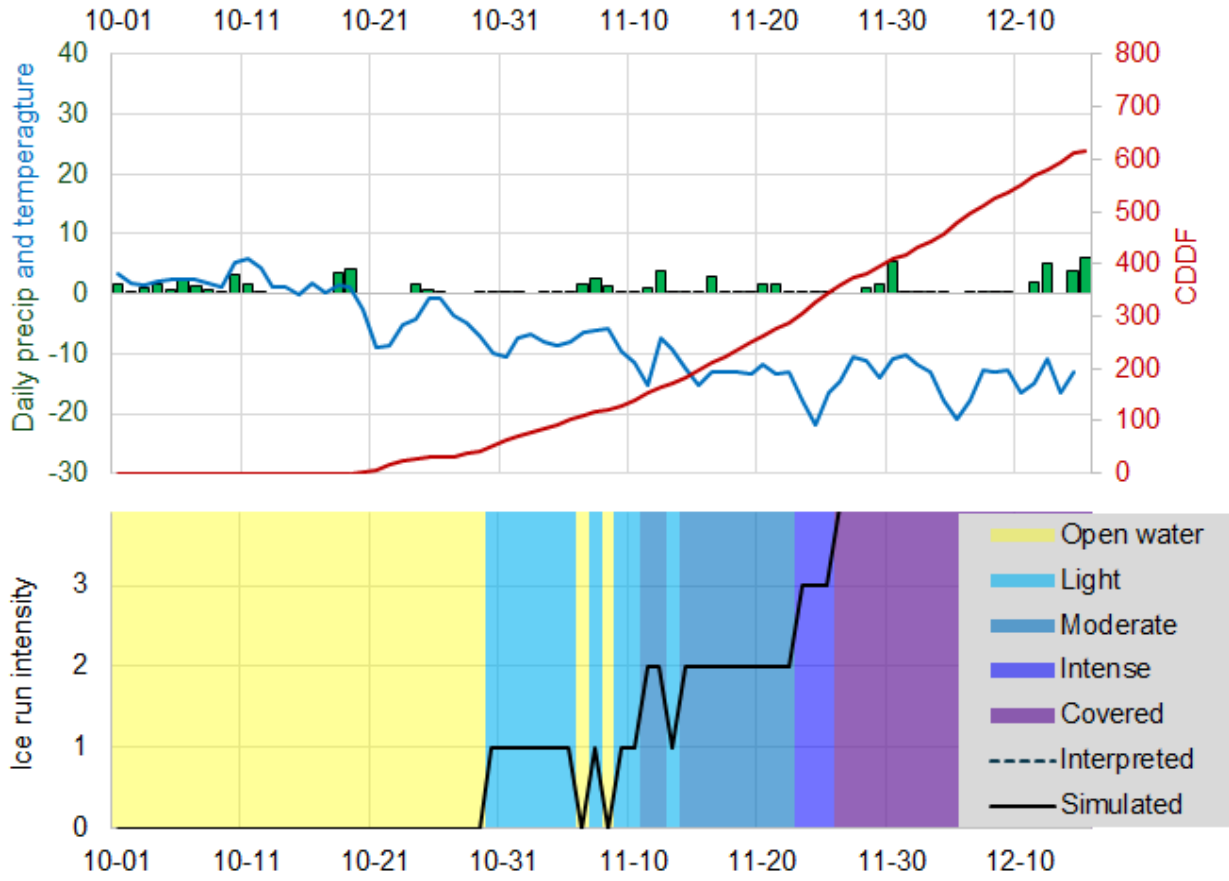
2035 (projections)



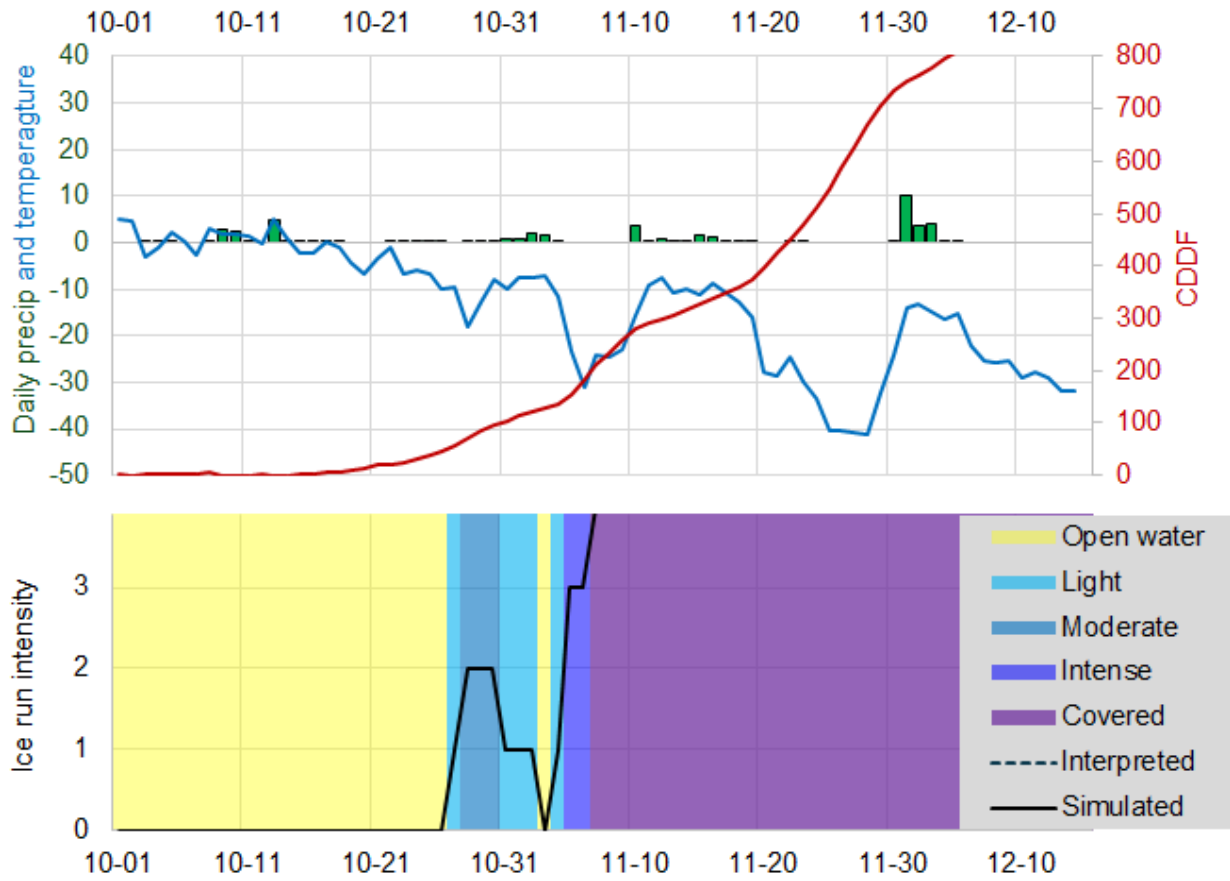
2036 (projections)



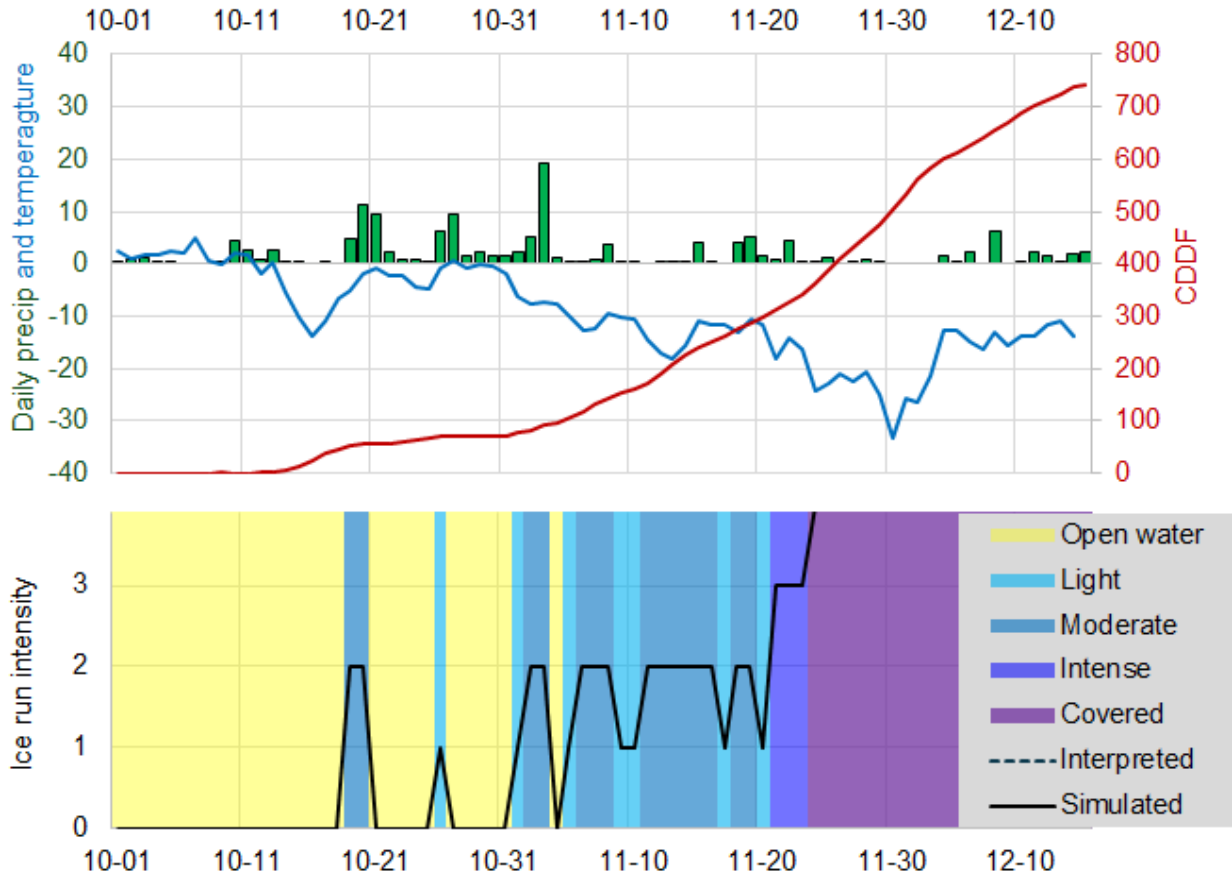
2037 (projections)



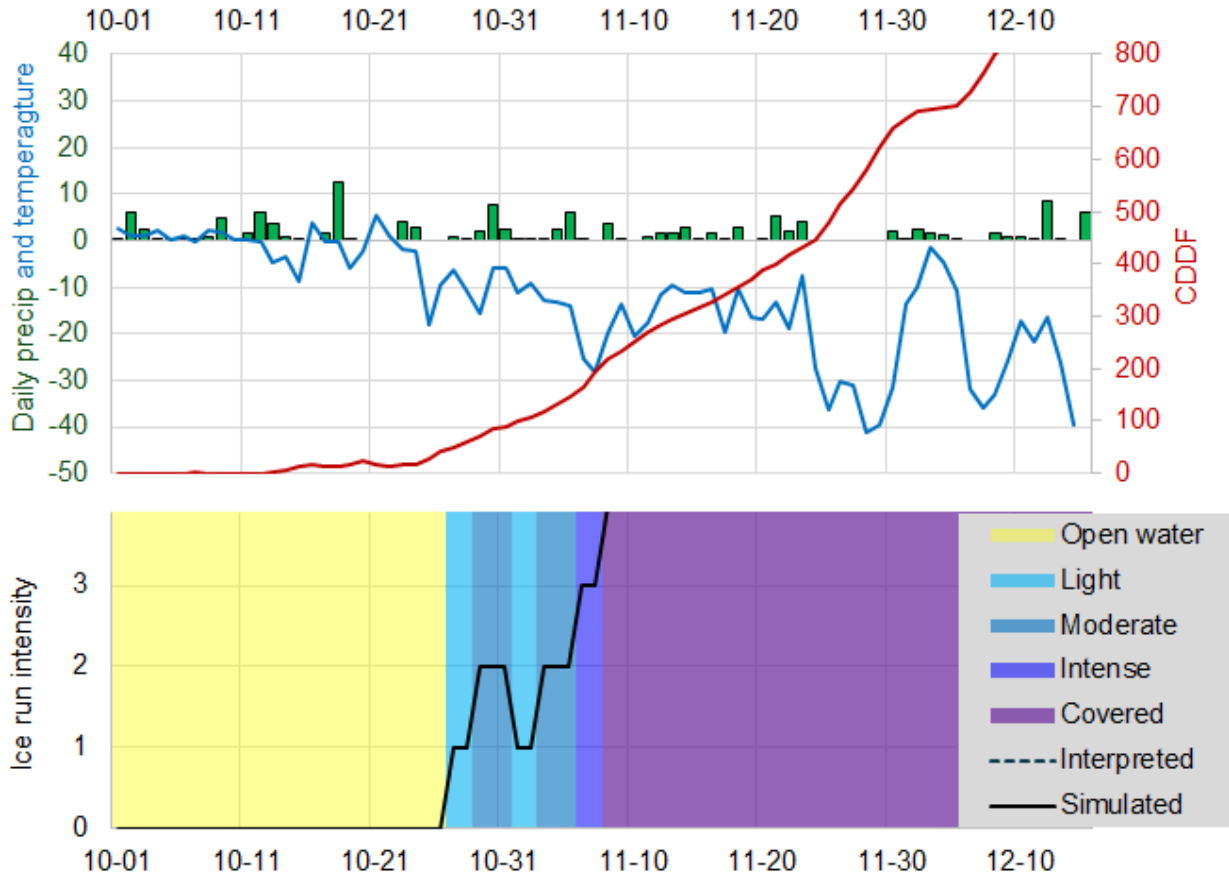
2038 (projections)



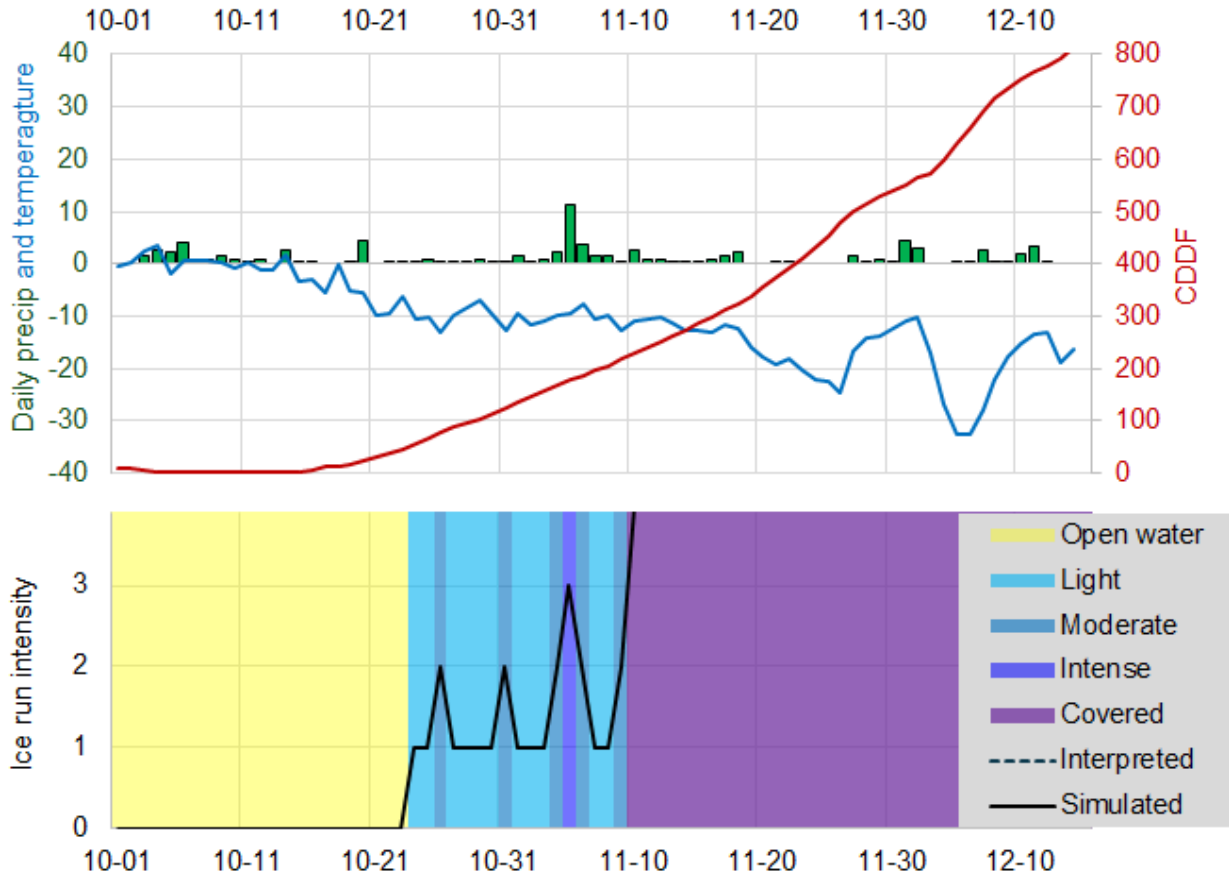
2039 (projections)



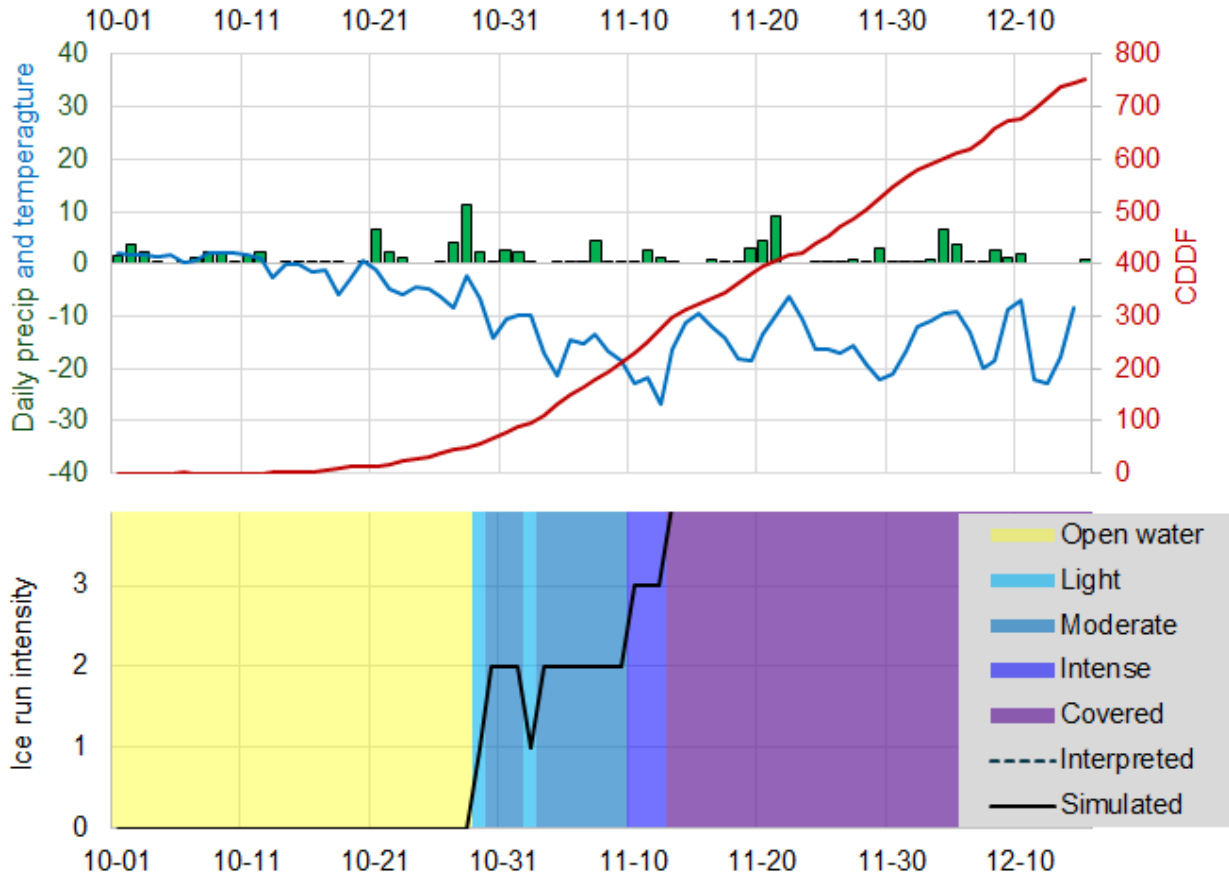
2040 (projections)



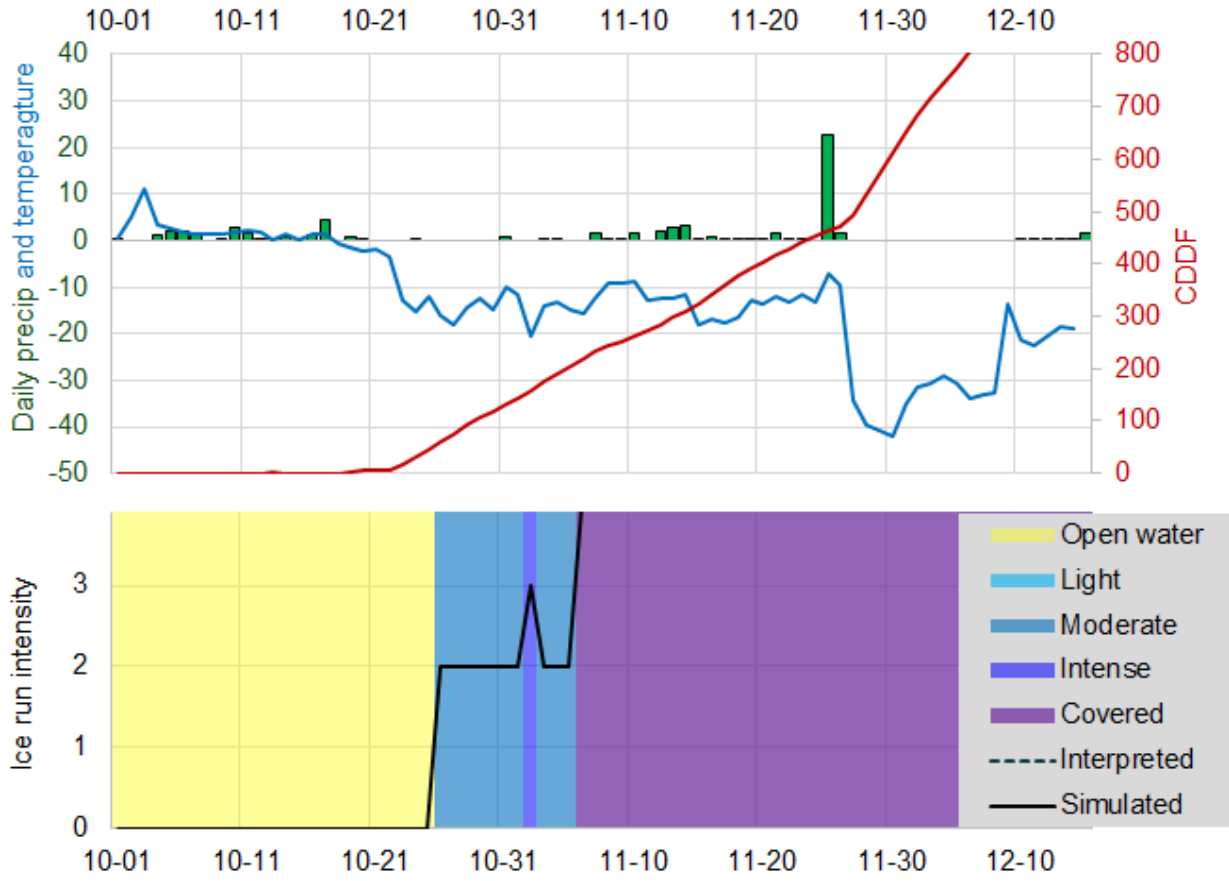
2041 (projections)



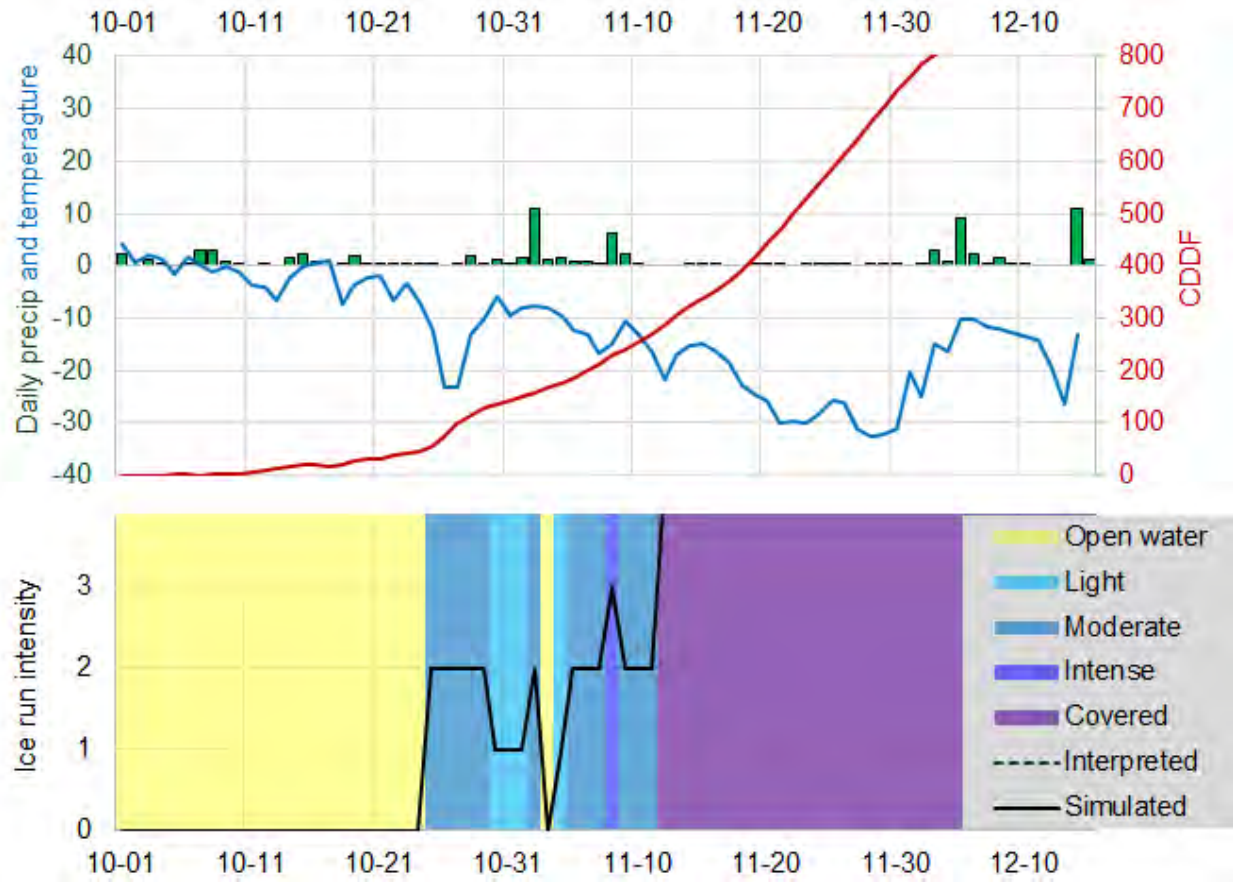
2042 (projections)



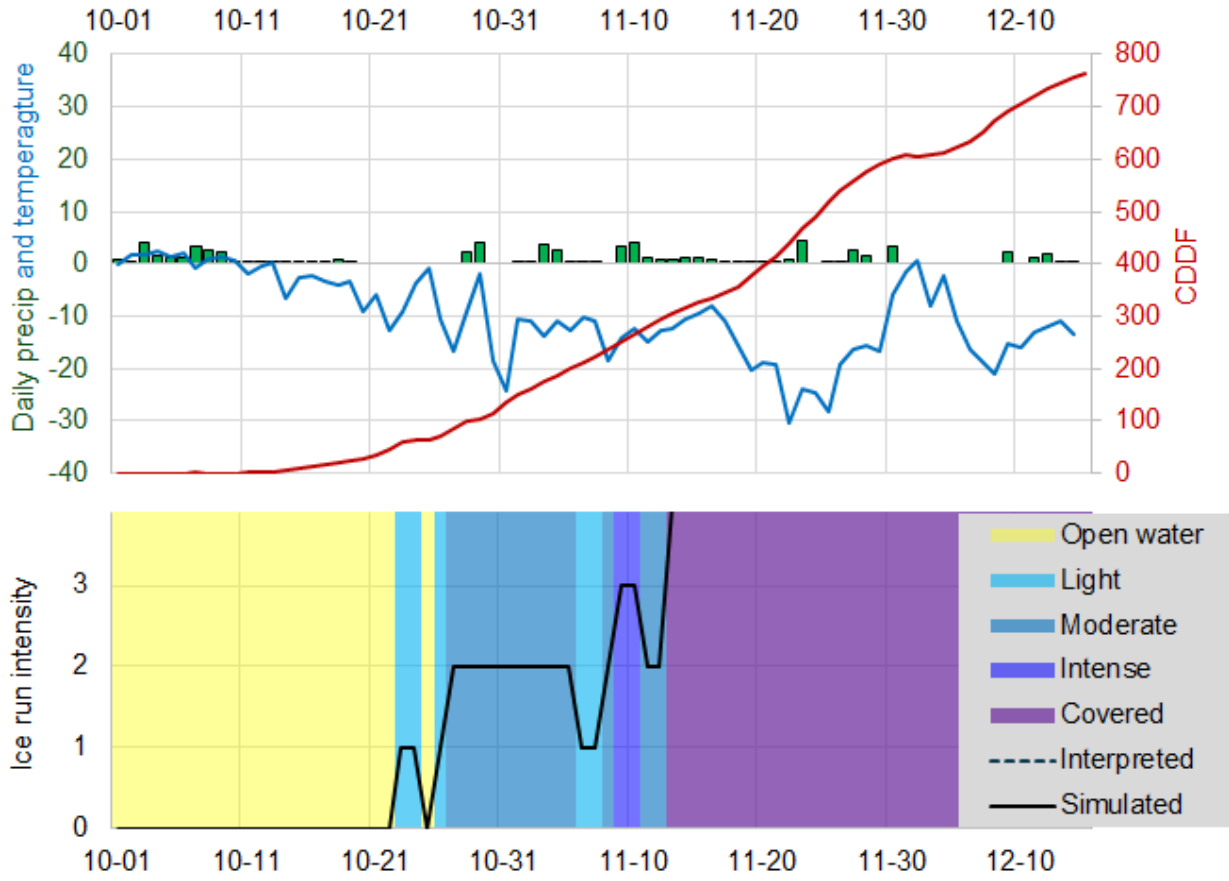
2043 (projections)



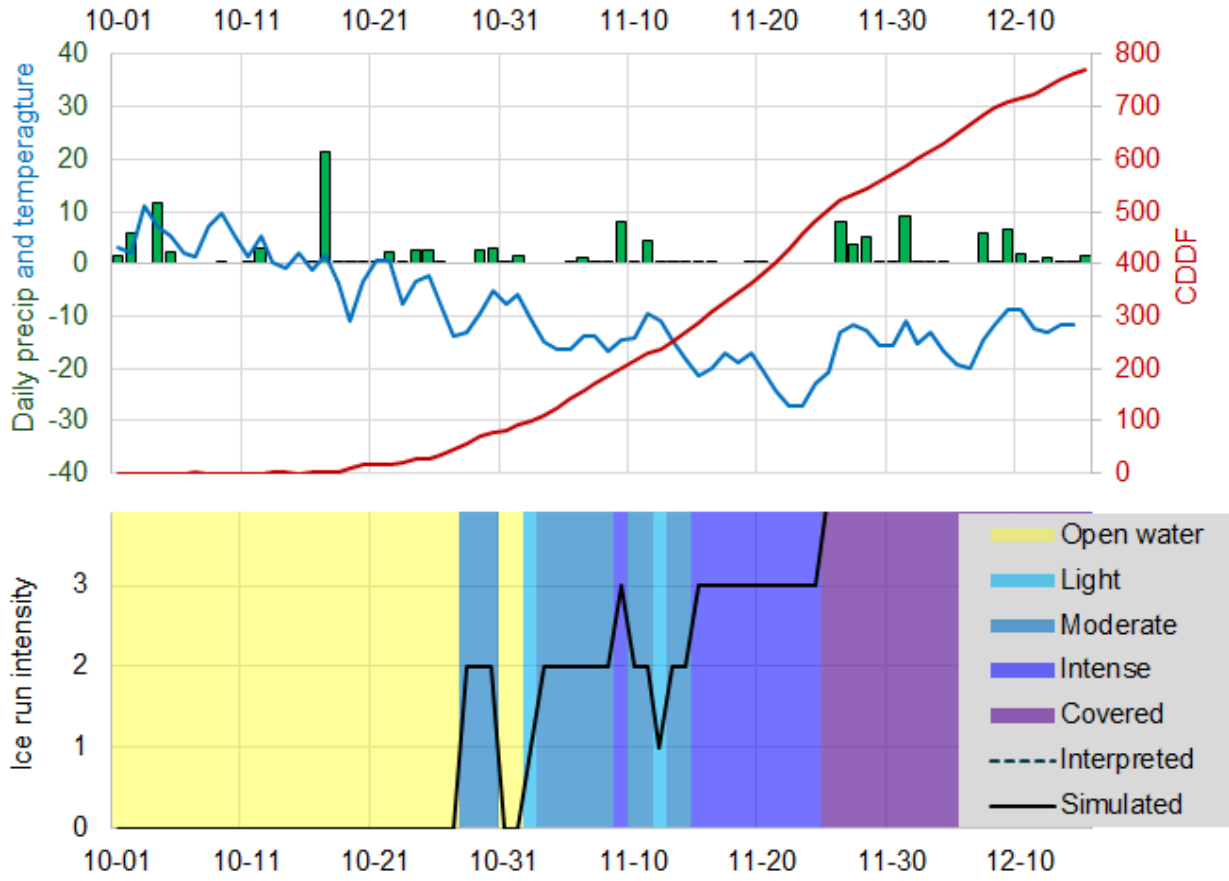
2044 (projections)



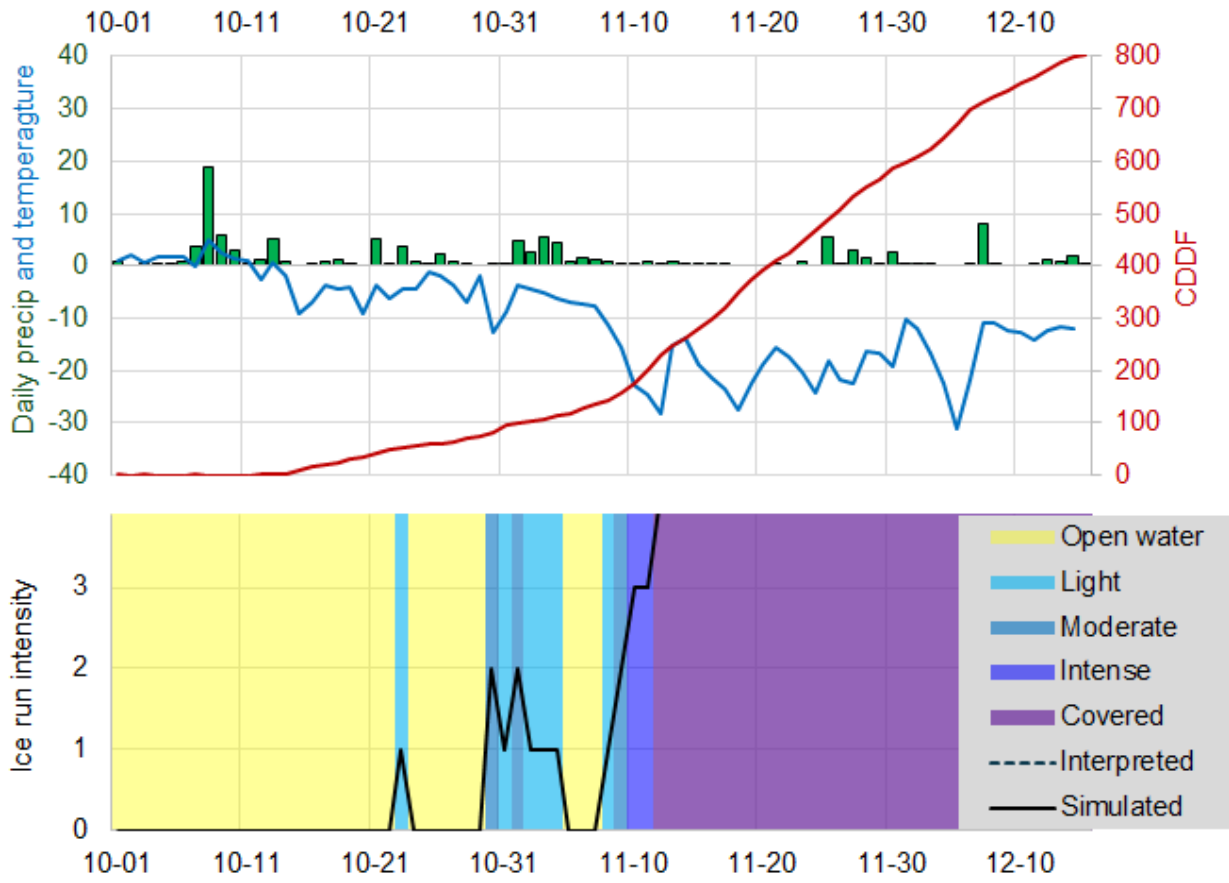
2045 (projections)



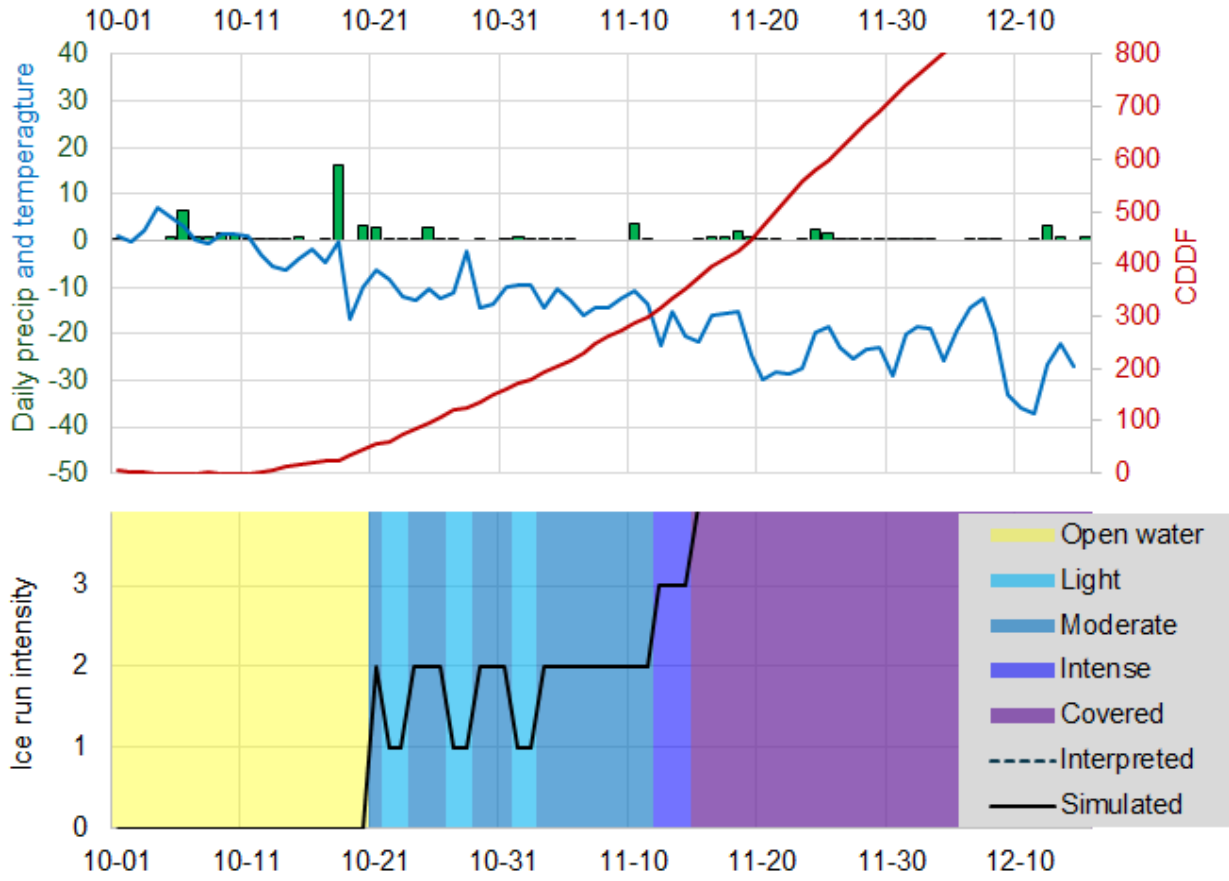
2046 (projections)



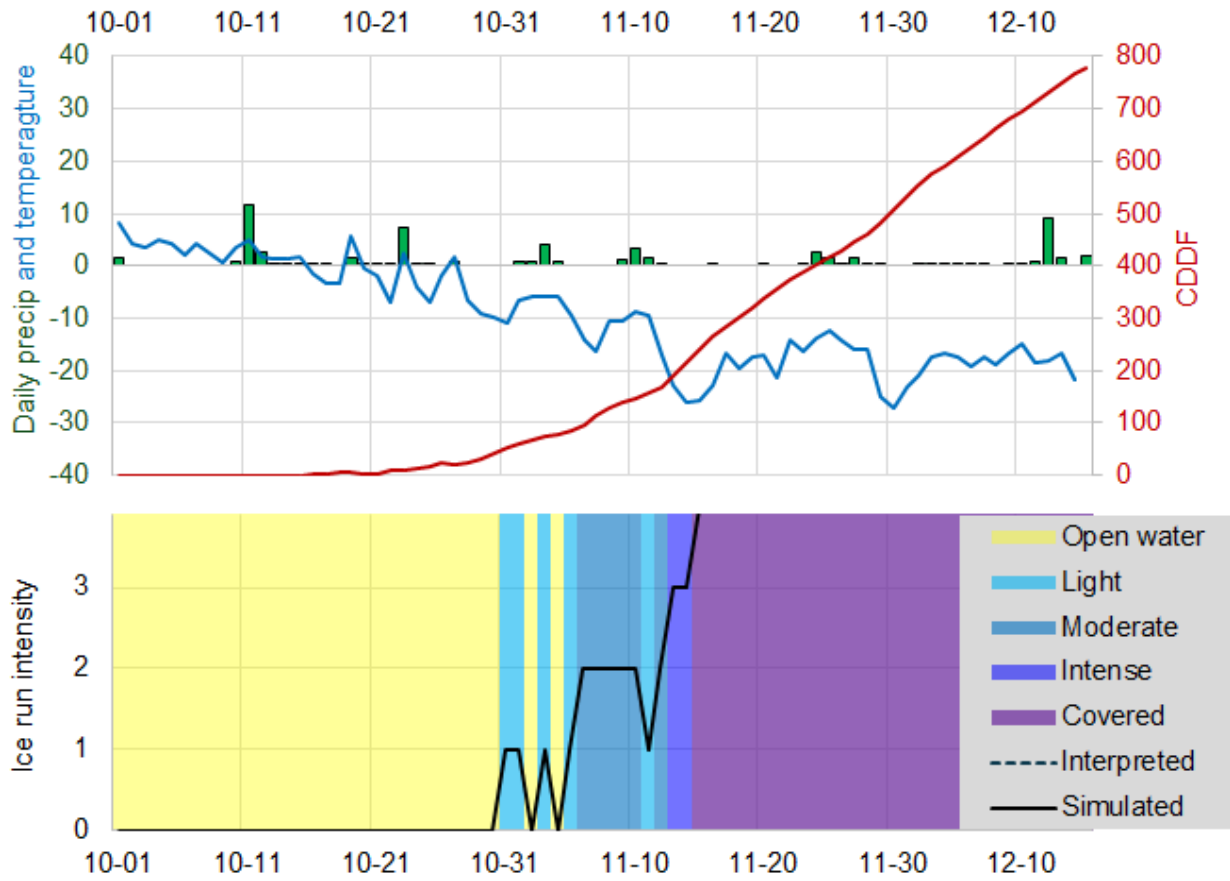
2047 (projections)



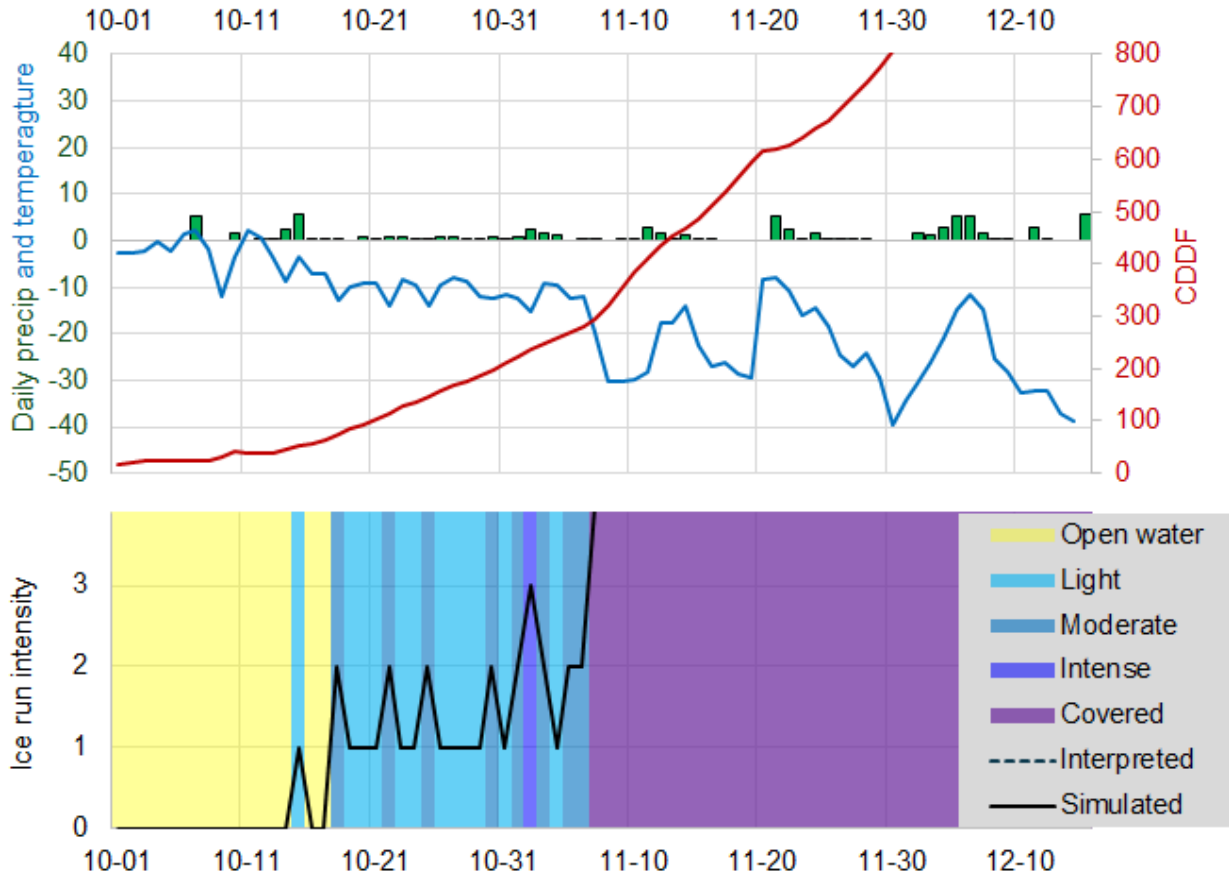
2048 (projections)



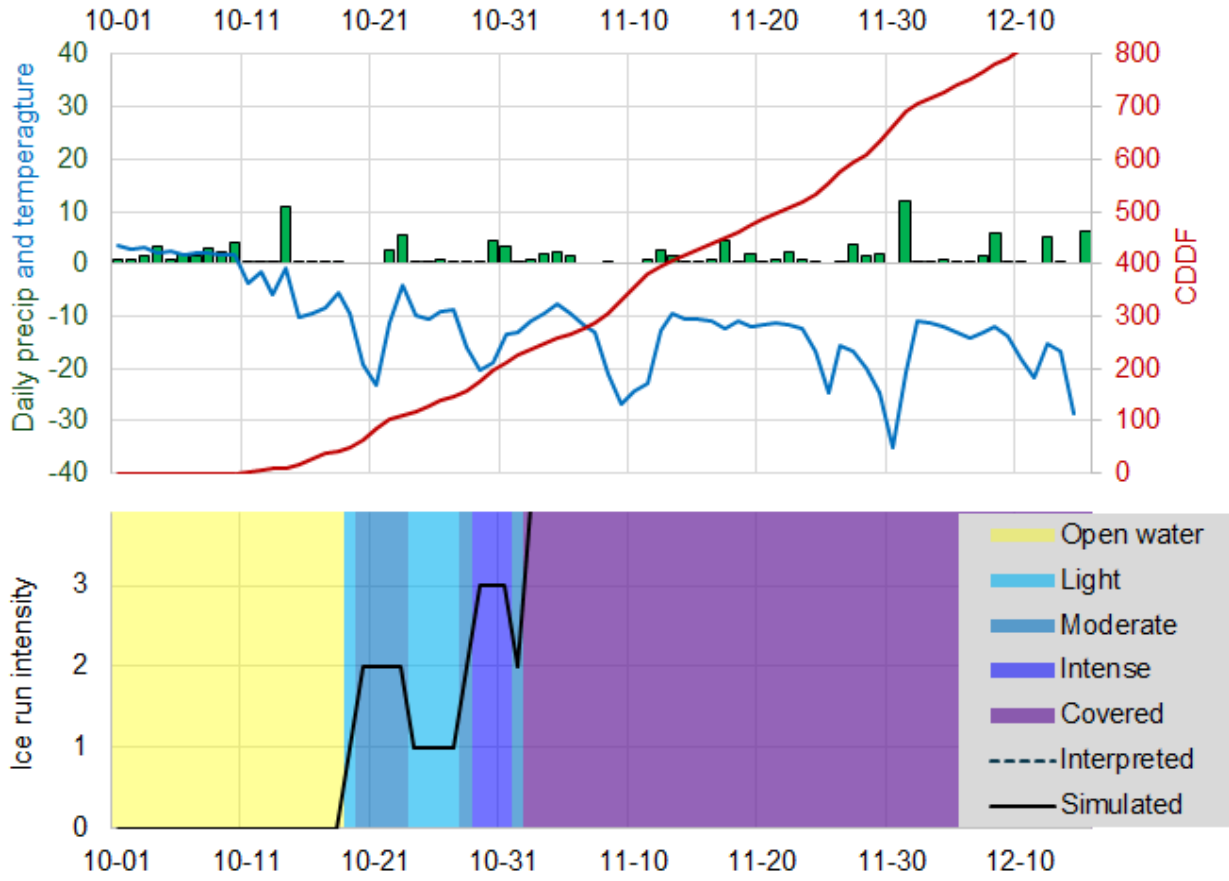
2049 (projections)



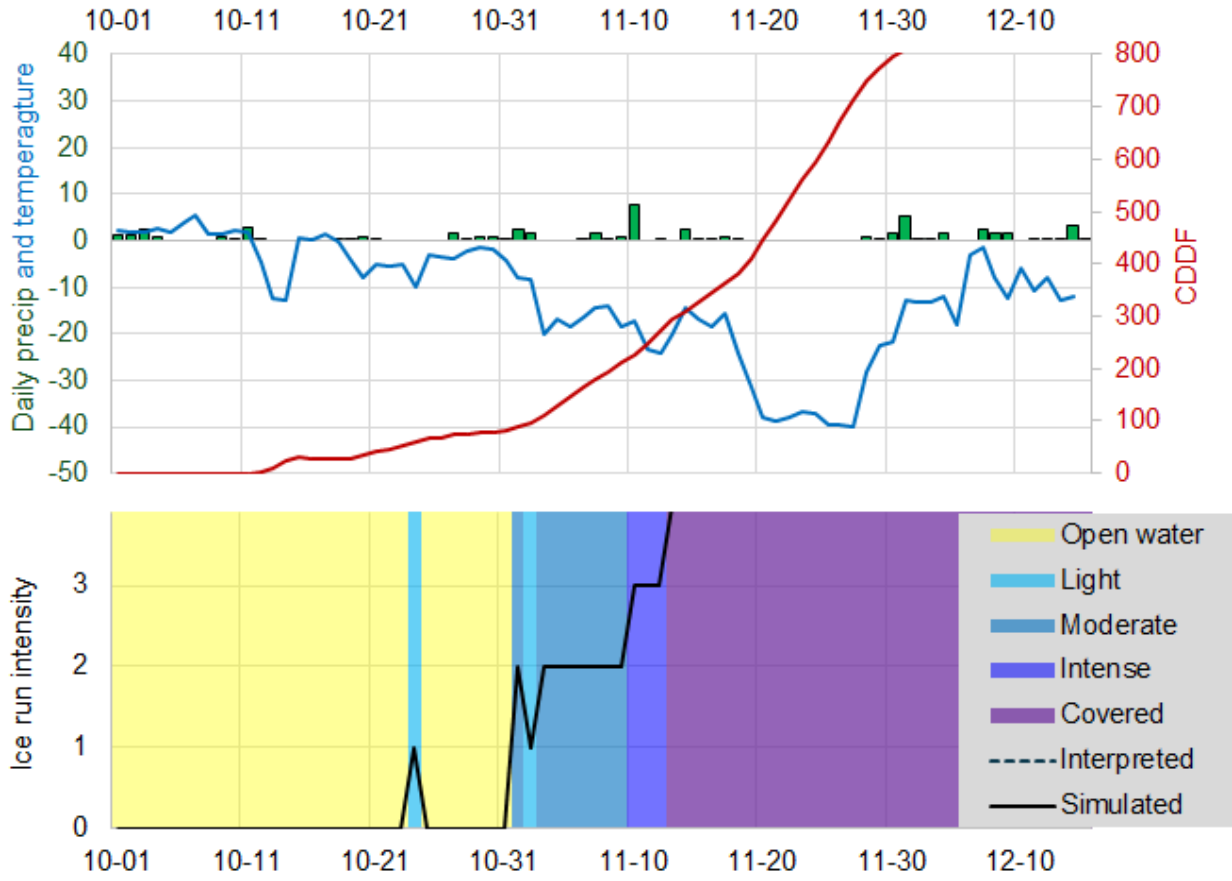
2050 (projections)



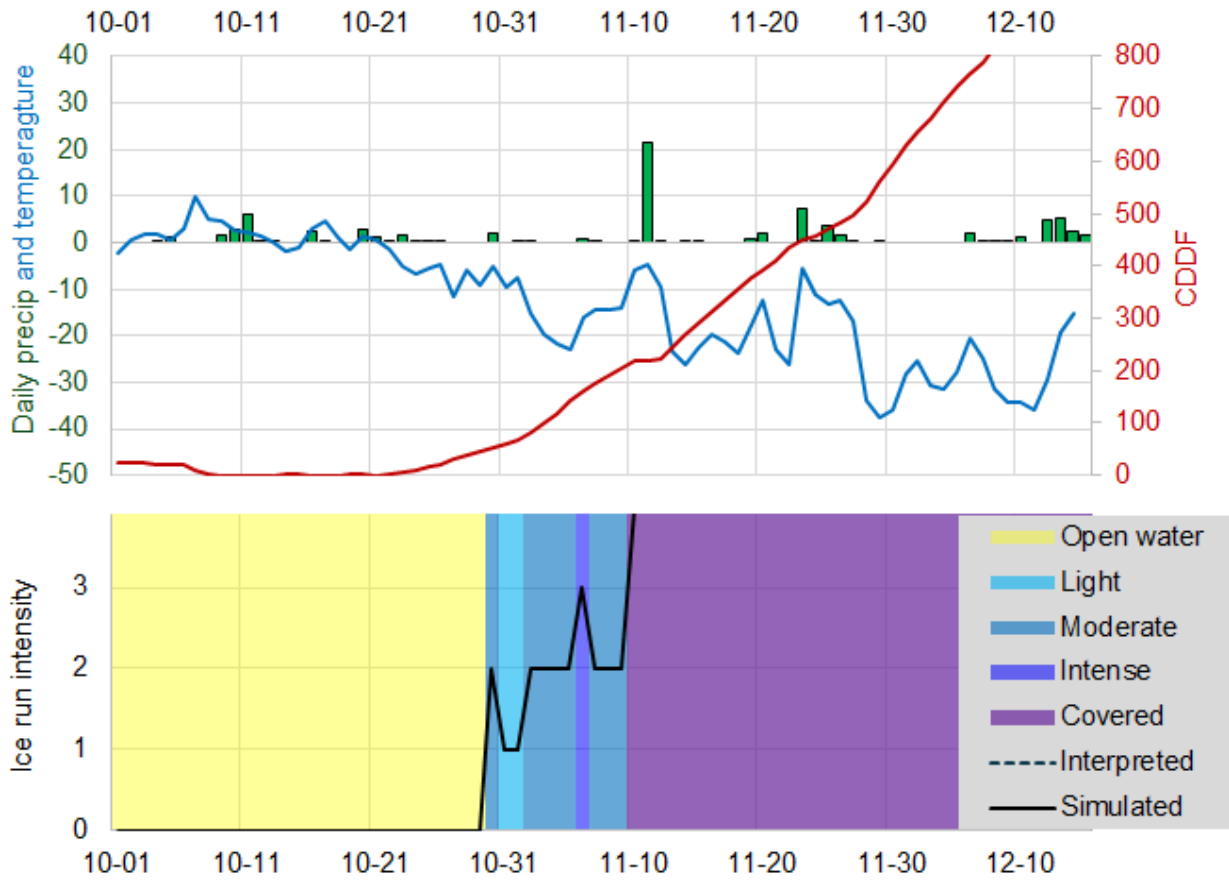
2051 (projections)



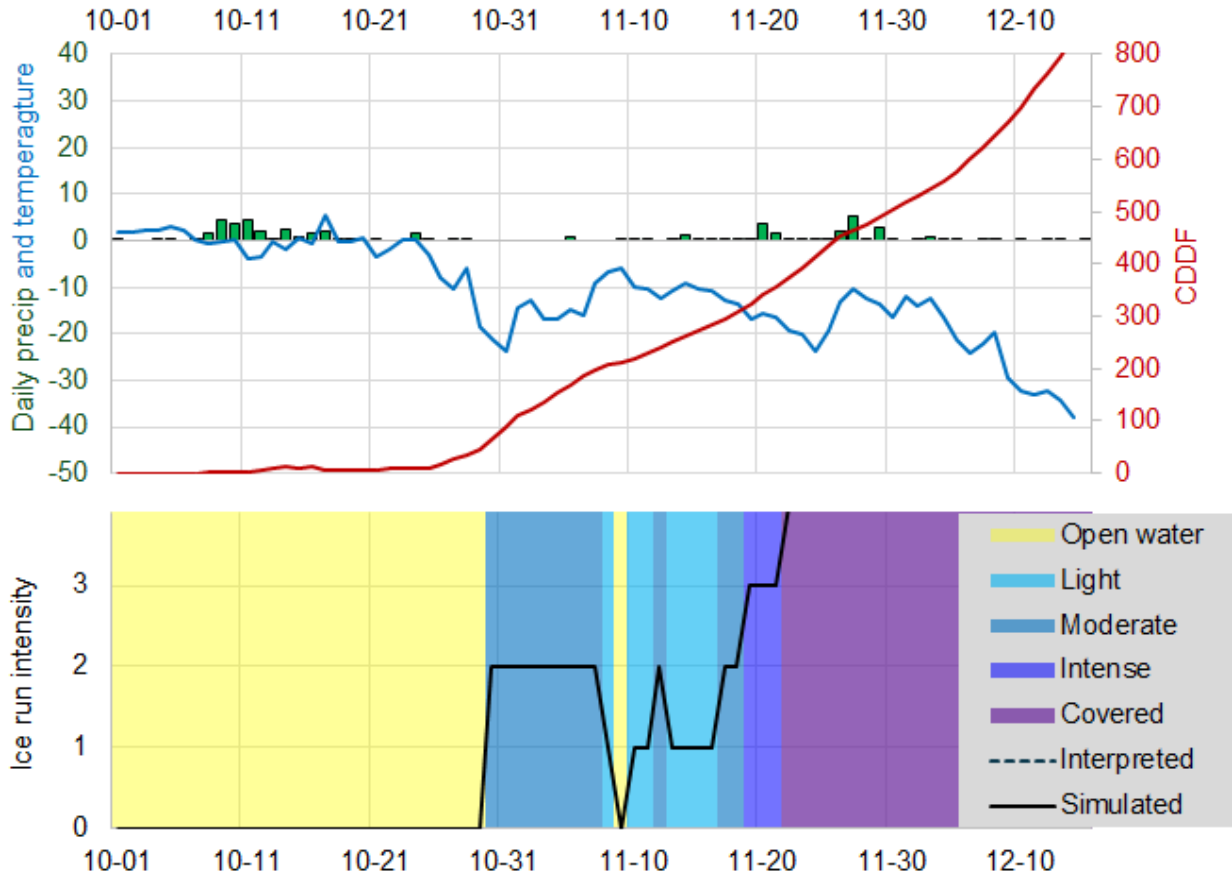
2052 (projections)



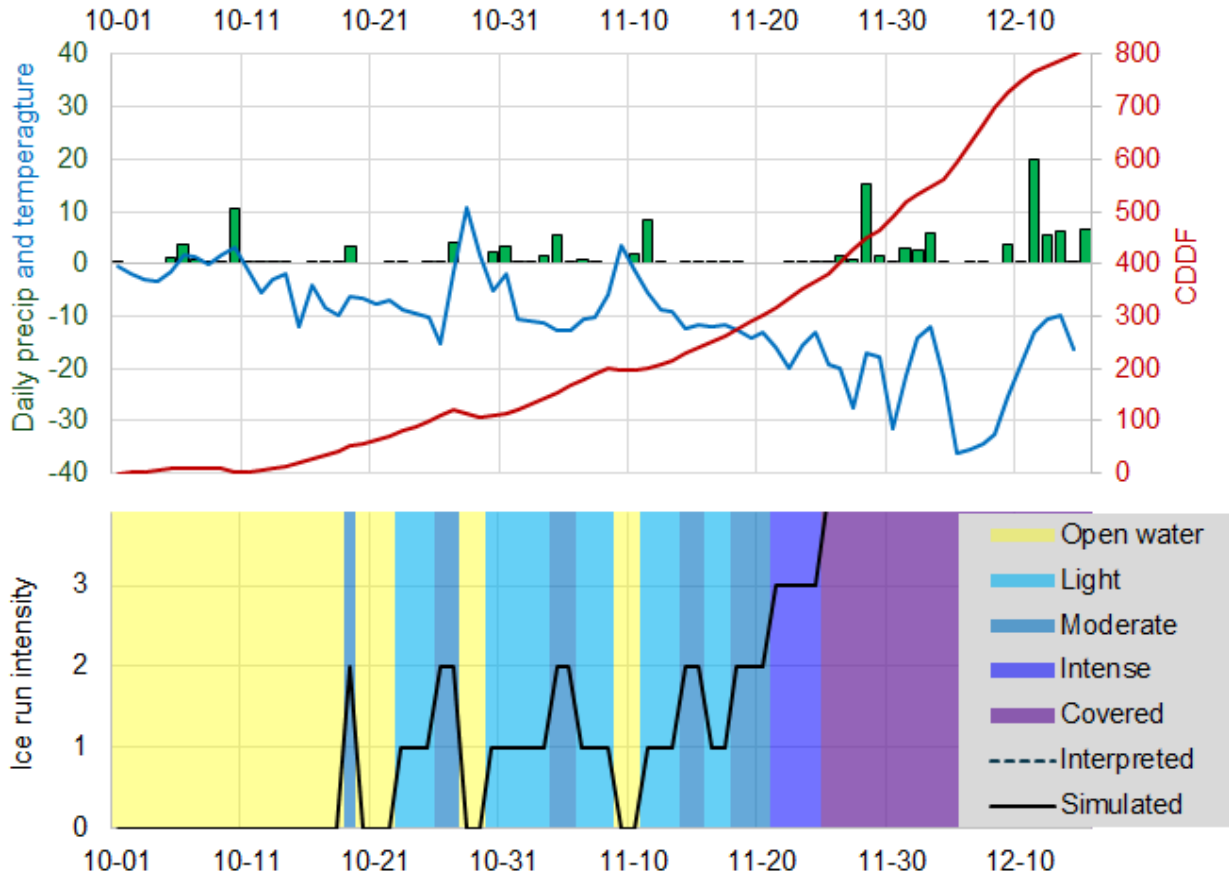
2053 (projections)



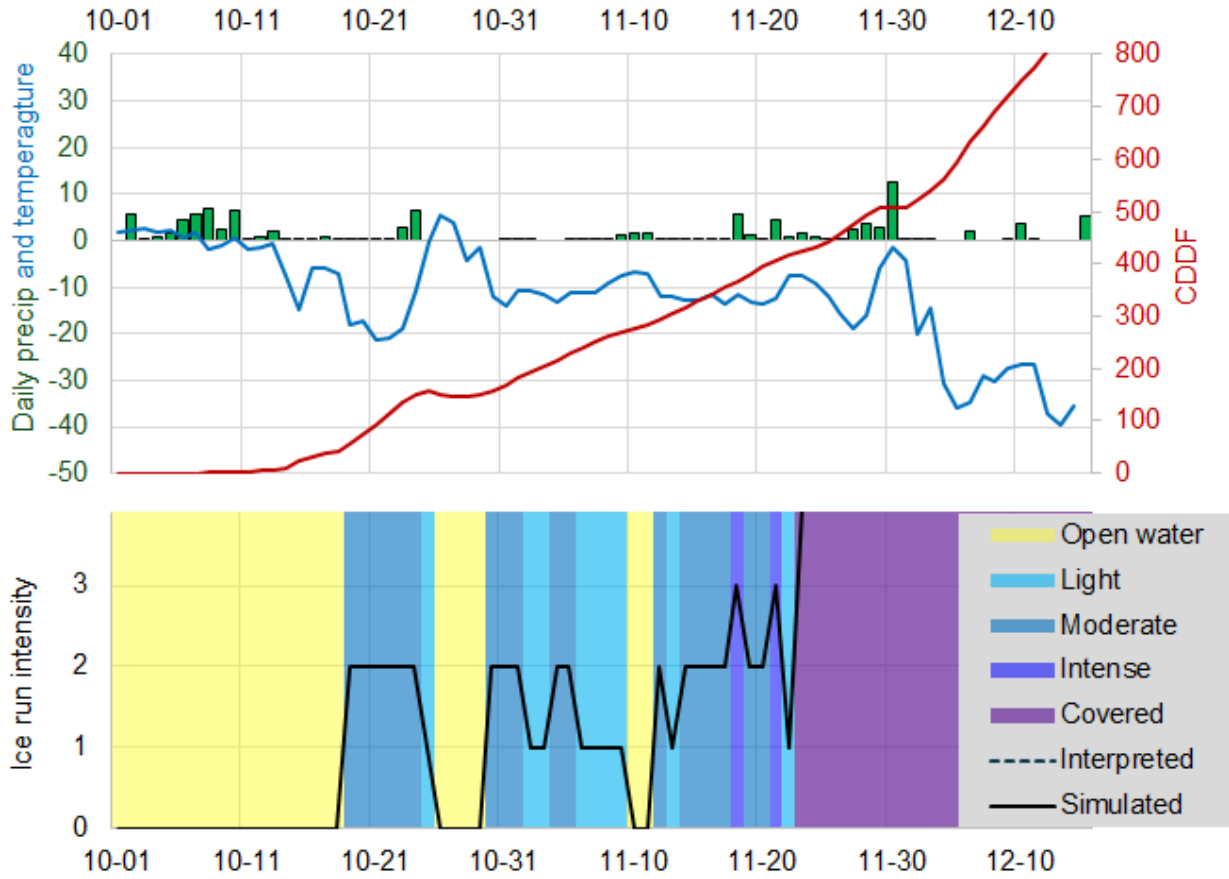
2054 (projections)



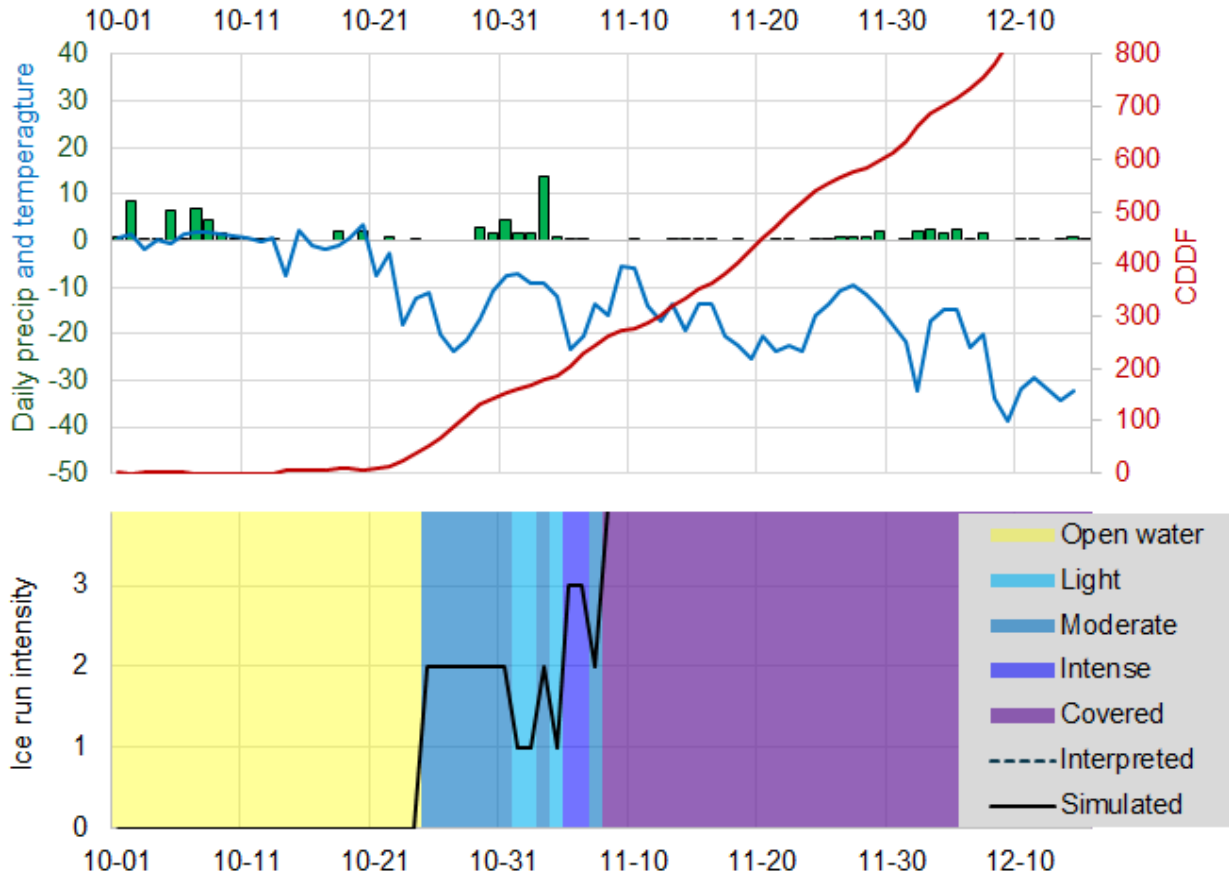
2055 (projections)



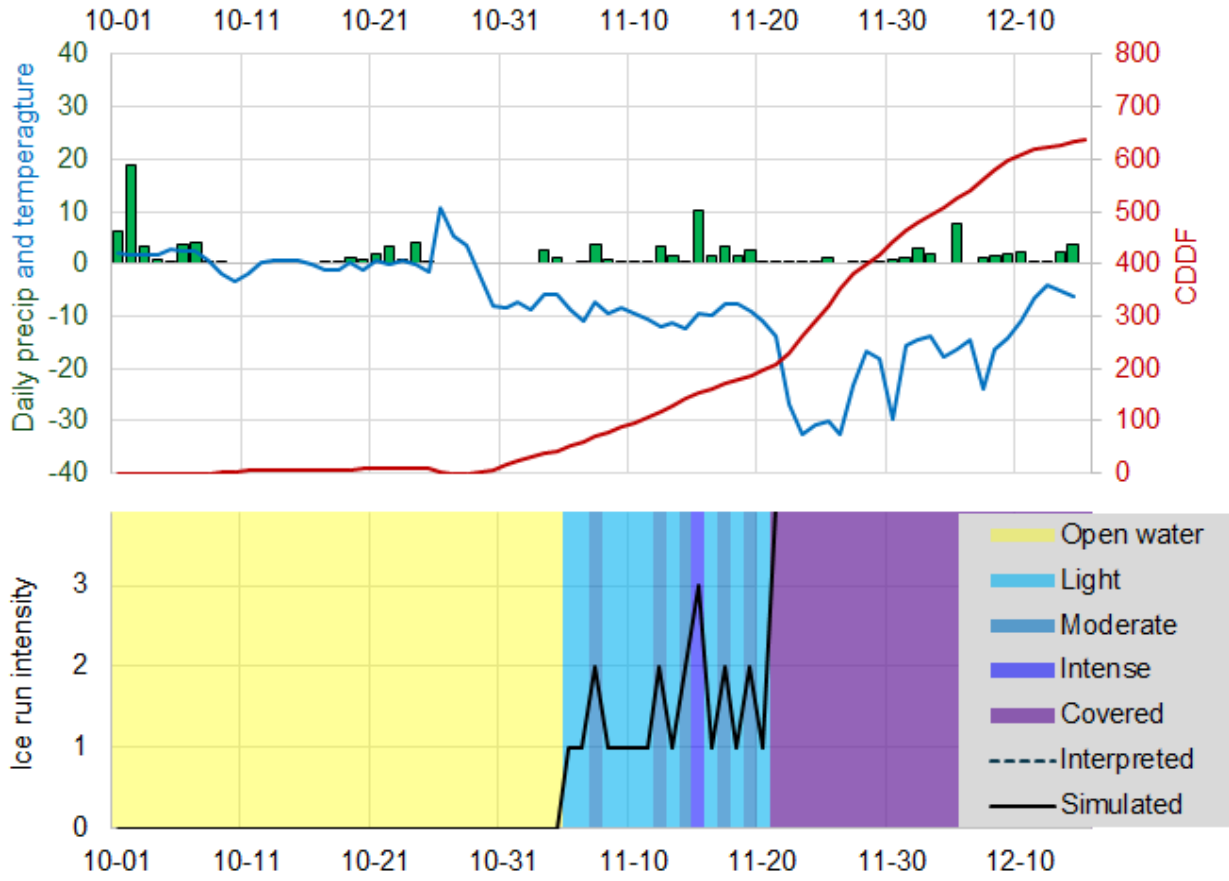
2056 (projections)



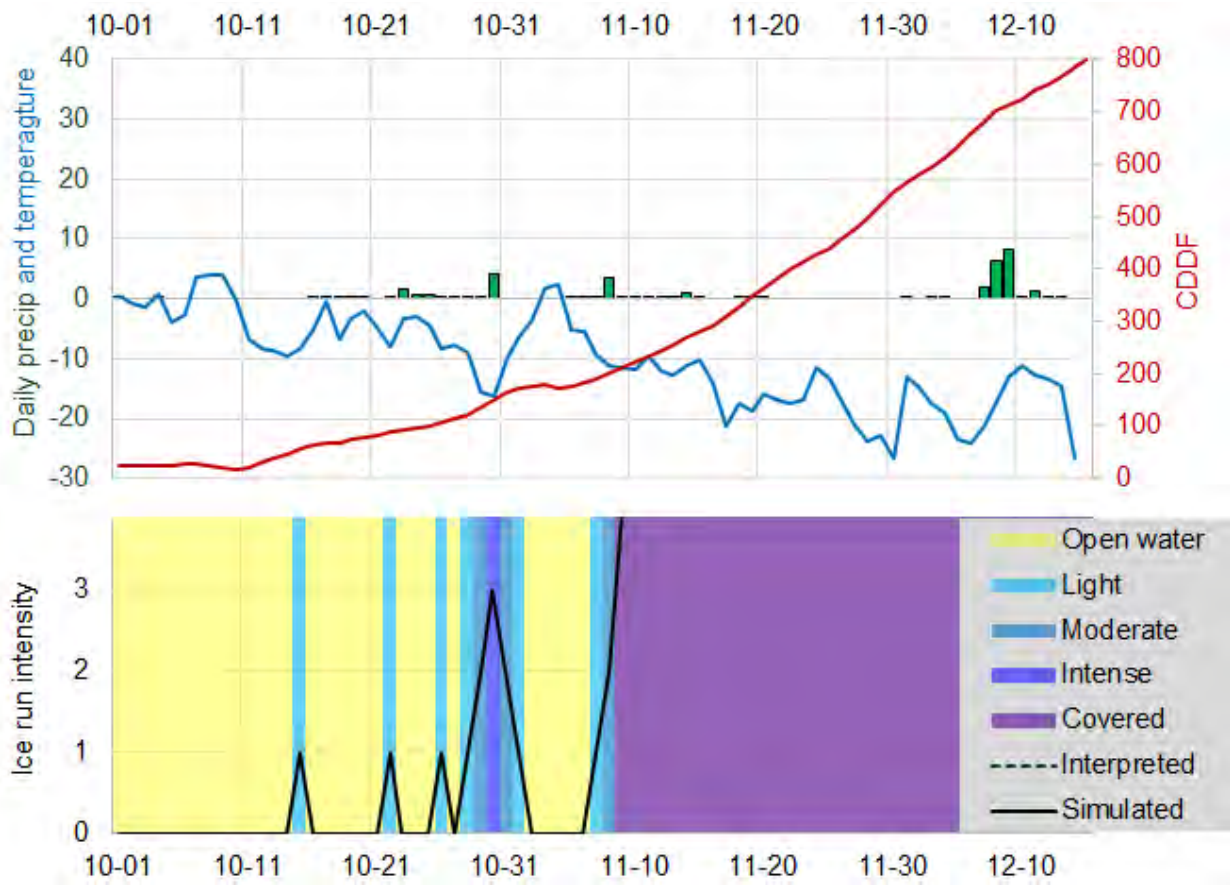
2057 (projections)



2058 (projections)



2059 (projections)



2060 (projections)

