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St. Lawrence Marine Corridor Climate Risk Information System: Preliminary Evaluation of Climate Change Impacts on Ice

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Executive Summary

Reliable predictions of future ice season severity and duration, storm surges, winds, wave conditions and water levels are not yet available for the St. Lawrence corridor region, and this data gap prevents effective assessment of climate risks and adaptation planning for the more than 100 ports and commercial docks on the Canadian and US coasts of the Great Lakes - St. Lawrence region that are served by the Seaway. A project is underway at the Ocean, Coastal & River Engineering Research Centre of the National Research Council of Canada (NRC-OCRE) to develop a climate risk information system for this region. Meeting this objective will enable more informed climate risk assessments for ports and other federally-owned transportation infrastructure. The present report focusses on the ice aspect only; a companion report covers the other variables of interest.

The work to date for the ice aspects has focussed on preliminary analysis of maximum annual thickness expected for the fast ice, i.e., ice that is attached to shore and not mobile. NRC mainly relied on a cumulative freezing degree day (CFDD) calculation – a relatively simplistic approach to estimate ice thicknesses. A collaboration was formed with McGill University, who provided climate modelling data. McGill's data used in the present report were air temperatures modelled assuming a high emissions scenario (RCP8.5, the warmest or "worst case"). The preliminary CFDD calculations using modelled air temperatures show a consistent trend of *decreasing maximum annual ice thickness* at all sites between 1990 and 2100, but with an *increase in relative variability* for future predictions. Preliminary work indicates that the maximum annual fast ice thickness at the end of this century could (on average) be half, or less, of the thickness values in the early 2000s, for all sites examined. Further analysis, refinement of methodologies, and statistical assessments will be performed in FY22-23 (the fiscal year ending in March 2023). The CFDD method may not be appropriate to use for future ice thickness assessments, or may require modifications, as it is heavily weighted toward historical conditions. The future predictions of ice thickness assume that only the air temperature changes; in reality, the future snow thicknesses and underlying water temperatures (amongst other factors) may also change enough to affect the expected ice growth. Further examination of the suitability of the CFDD method would be useful. The results should also be compared with those from thermodynamic or climate modelling.

Data from on-ice measurements and the CFDD approach were compared for the period of 1990 and 2010 during which measurements were made, in an attempt to validate the historical CFDD results. While the CFDD calculations were in the same range as on-ice measurements, correlation of annual maximum ice thickness is low. The small sample size makes correlation assessments difficult. Predicted fast ice thicknesses at all sites show a large degree of inter-annual variability – and this is supported by the historical on-ice thickness measurements.

At one selected site near Montreal, additional analysis was done to compare on-ice thickness measurements (1970-1997), CFDD calculations using modelled air temperatures (1990-2009), CFDD calculations using measured air temperatures (1970-2000), and preliminary climate modelling of ice thickness by McGill (1990-2009). All methods indicate thinning of the ice over that historical period. Testing for statistical significance was not performed. Further assessments will be performed in FY22-23.

Some initial thermodynamic modelling was carried out to begin the assessment of fast ice season duration. NRC's thermodynamic model showed good agreement with ice measurements for selected historical years. Further testing, and possible refinement, is needed for McGill's implementation of the FLake model. Initial

comparison of FLake results to historical ice measurements was not encouraging, necessitating the use of NRC's thermodynamic model.

The analysis presented in this report is preliminary. Methodologies are presently being refined and the final assessments of fast ice thicknesses (hindcast as well as future values) will be presented in a second report to be produced before March 2023. That report will also include analysis of fast ice season duration.

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1. Introduction

Reliable predictions of future ice season severity and duration, storm surges, winds, wave conditions and water levels are not yet available for the St. Lawrence corridor region, and this data gap prevents effective assessment of climate risks and adaptation planning for the more than 100 ports and commercial docks on the Canadian and US coasts of the Great Lakes - St. Lawrence region that are served by the Seaway. A project is underway at the Ocean, Coastal & River Engineering Research Centre of the National Research Council of Canada (NRC-OCRE) to develop a climate risk information system for this region. Meeting this objective will enable improved climate risk assessments to be developed for several important ports and other federally-owned transportation infrastructure. The climate risk information developed in this project will also be of considerable interest to other regional stakeholders such as ship operators and owners of waterfront infrastructure. One component of the new climate risk information system will be data on past and future ice conditions; the focus of the present report is a preliminary analysis of such data.

1.1. Background

Ice conditions, storm surges, water levels, winds and waves are key climate-driven parameters affecting maritime shipping and the design and operation of ports and other transportation infrastructure in the lower St. Lawrence River and Gulf region (the St. Lawrence Marine Corridor). As a consequence of climate change, these parameters are expected to change in the future. Over the past 70 years, temperature has increased in all regions of Canada including its oceans, and further warming is predicted in all seasons (Bush and Lemmen, 2019).

Many environmental factors influence the maintenance, operational efficiency, safety and resilience of ports, harbours and other waterfront infrastructure in the lower St. Lawrence River and Gulf, including the frequency and magnitude of strong winds, excessive wave conditions, extreme high water levels, the duration of the ice season and the severity of mid-winter ice conditions. These are primary considerations for the planning and design of new port facilities, and expansion or adaptation of existing facilities, as well as for the design, maintenance and safety of water-spanning bridge structures. These factors can affect cargo-handling efficiency and berth downtime, navigation risk and safety, pollutant spill risk and response capacity, and risks to ships and port structures from coastal hazards (waves, ice, currents, flooding, erosion, and tsunami). Changes to the various environmental factors, due to climate change, could shorten the useful life of many infrastructure systems and increase requirements for maintenance or renewal.

Figure 1 shows locations of many of the existing infrastructure assets on the St. Lawrence Marine Corridor. Virtually all existing infrastructure was designed to withstand historical local weather and climate; however, due to climate change, the historical climate is no longer a reliable predictor of the future. Climate change is projected to increase the intensity of some extreme weather events and alter climate-driven variables such as water levels and wave conditions. Ice presence and thickness, meanwhile, are generally expected to decline (although changes to other factors, such as air temperature, due to climate change can make events like ice jams more likely).

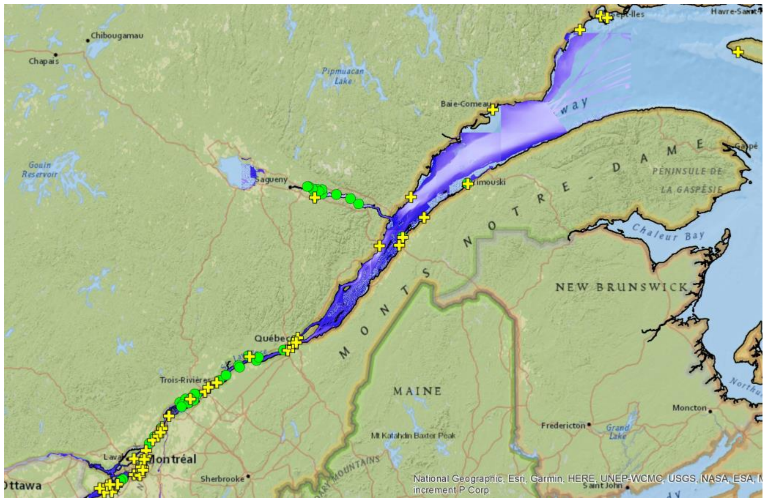

Figure 1. Sites in the St. Lawrence River and northeast Gulf where infrastructure assets are located (yellow crosses), and where systematic ice thickness measurements have been made (green dots). Bathymetry is indicated in purple.

1.2. Objectives

NRC has previously created the Canadian Coastal Climate Risk Information System for Western Canada's coastal regions (https://cccris.ca/). Under the present project this system is being expanded to include the expected impacts of climate change on ice conditions, storm surges, winds, wave conditions and water levels throughout the St. Lawrence River and Gulf, from the Beauharnois Dam upstream of Montréal to Île d'Anticosti north of Gaspé.

The project objectives, as they relate to ice, involve the evaluation of climate change impacts on ice season severity and duration, including:

- Statistical analysis of historical trends in ice season duration and severity
- Prediction of climate change impacts on ice conditions for selected climate change scenarios and time horizons
- Statistical analysis of future values (including extremes) for ice thickness, ice concentration, freeze-up, break-up, and ice season duration.

The expected final deliverables related to ice are:

- Preliminary climate parameter database on ice, which will be incorporated into the Canadian Coastal Climate Risk Information System in FY2022-23
- Preparation of a conference and/or journal paper describing the work and the key outputs.

The present document is an interim report on the above ice information and considerations for the Canadian Coastal Climate Risk Information System. A second report will be produced in FY2022-23, including further assessments of future ice thickness and ice season duration. That report will describe the ice variables which will be included in the Canadian Coastal Climate Risk Information System.

2. Understanding ice growth and dynamics in the St. Lawrence marine corridor

When ice grows outward from the shoreline and remains stationary (attached to the shore, or otherwise pinned), it is referred to as *landfast ice, shorefast ice* or simply *fast ice*. Fast ice can, over the course of a winter, extend out many kilometers from shore and achieve a considerable thickness. In a lake, the entire surface may freeze. In a river or in the open ocean, the lateral extent of fast ice is often limited by water movement. Lake and river ice are composed of fresh water, while sea ice is the outcome of seawater freezing and contains salts. For the purposes of this study, the main difference is that sea ice will freeze at a lower temperature, since salts depress the freezing point of water. Sea ice is also mechanically weaker than freshwater ice due to the entrapped impurities.

In the ocean or a large river, the ice beyond the fast ice edge is dynamic and consists of slabs of ice called *floes*. In the sea, this mobile ice is known as pack ice or drift ice. Sea ice in its first growth season is known as first-year ice (FYI). If the ice survives a summer melt season into the next winter, it is known as second-year ice, and, subsequently, multi-year ice (MYI). Second-year and multi-year ice do not exist in the regions discussed in the present report; nor do icebergs. Figure 2 gives a schematic of some sea ice types and processes. For more information about ice classifications and formation the reader is directed to MANICE (2005). In the St. Lawrence River it is Canadian practice to use sea ice terminology down river from St. Lambert lock (i.e., Montreal area) and lake ice terminology up river from St. Lambert lock.

Along the entire St. Lawrence River, *batture ice* can form in the shallows due to tidal action. Ice of different thicknesses is pushed together on the upstream side of a shoal or islet during ebb tides; the whole mass freezes and gradually increases in size with each successive tide. As the tidal range increases between neaps and springs, large sections of grounded ice can break away from shore and drift down the river. Batture ice floes represent a significant hazard to shipping (Fowler, 2020).

Ice growth is a function of complex heat transfer processes which relate to air temperature, snow depth, relative humidity, wind speed, solar radiation, ocean heat flux, etc. The present report covers mainly fast ice. The dominant factor for fast ice formation is air temperature, with snow depth being secondary.

Mobile ice is strongly influenced by winds and ocean currents, which result in ice dynamics and deformation. Individual ice floes can move and interact with each other to form pressure ridges or open water leads. Assessments of pack ice thickness evolution are therefore more complex than those for fast ice.

Another ice-related problem on the St. Lawrence marine corridor is ice jams. An ice jam occurs when ice accumulations restrict water flow in a river, and can lead to flooding of nearby land. The ice accumulations consist of broken river ice or sea ice; batture ice can contribute to this (Canadian Coast Guard, 2012). Ice jam flood timing and likelihood of occurrence are likely to be affected by climate change (Turcotte et al., 2019; Rokaya et al., 2018).

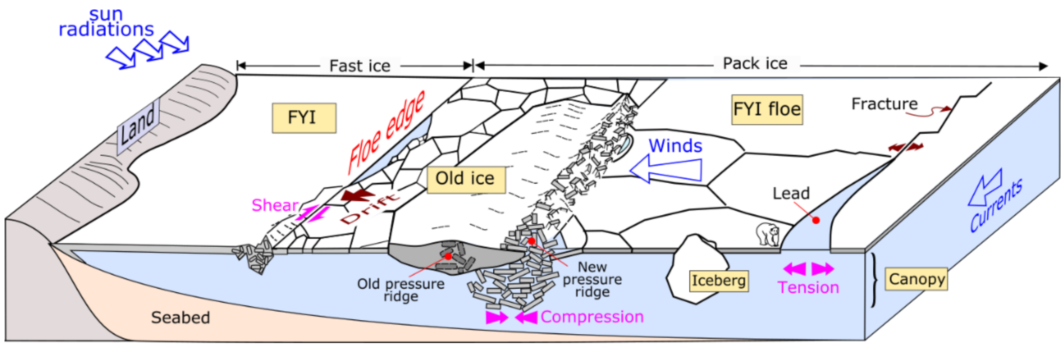

Figure 2. Simplified example of some sea ice types and processes (reproduced from Barrette and Sudom, 2022)

In addition to the “natural” ice formation and retreat mechanisms that occur, the ice of the St. Lawrence marine corridor is affected by vessel traffic and man-made structures. These serve to change the thickness, composition and movement of ice in some areas. The following paragraph is a summary of operations in the marine corridor provided by retired CCG Captain David Fowler for a previous project (Fowler, 2020):

> A large number of vessels travel [from the Gulf] up the St. Lawrence River as far as Montreal throughout the year, even in the winter months. An extensive Canadian Coast Guard icebreaking program supports this maritime traffic and other interests along the river. Minimal icebreaking is required on the Seaway [upstream of Montreal to Lake Ontario] because it is shut down from approximately late December to late March yearly... On the St. Lawrence River part of the Seaway, ice booms are put out each year to protect hydroelectric facilities from ice damage. Ice movement is controlled by use of these booms along with some control of water current by varying water flow through dams. In some areas, the ice clears out from bank to bank due to the current. In other river areas, there is fast ice along the shores. There are some big lake sections in the river, including Lake St. Lawrence, Lake St. Francis, Lake St. Louis and below Montreal, Lake St. Pierre. If icebreaking is required, tracks are cut along the channels and the fast ice in the rest of the lake is left intact as long as possible. At some point in the spring, Canadian Coast Guard hovercraft are used to break up this fast ice and allow it to flow downriver at a controlled rate.

Icebreakers work to fracture the fast ice into discrete floes, so that other vessels can follow in the wake with lower risk of ice damage. Icebreaking activity can also create *brash ice* – an accumulation of other forms of ice broken into small (less than 2 m) pieces. Brash in a vessel wake can consolidate (refreeze) to create ice that is thicker and more difficult to transit than the surrounding unbroken ice. The time required for this consolidation is affected by air temperature and wind conditions.

The Canadian Ice Service, part of Environment and Climate Change Canada (ECCC), produces ice charts throughout the shipping season showing the actual ice conditions observed and/or interpreted by ice analysts; an example is given in Figure 3. Note the large grey areas indicating that fast ice covers most of the lake. The shipping channel is visible as colour-coded areas indicating mobile ice of various thicknesses and concentrations.

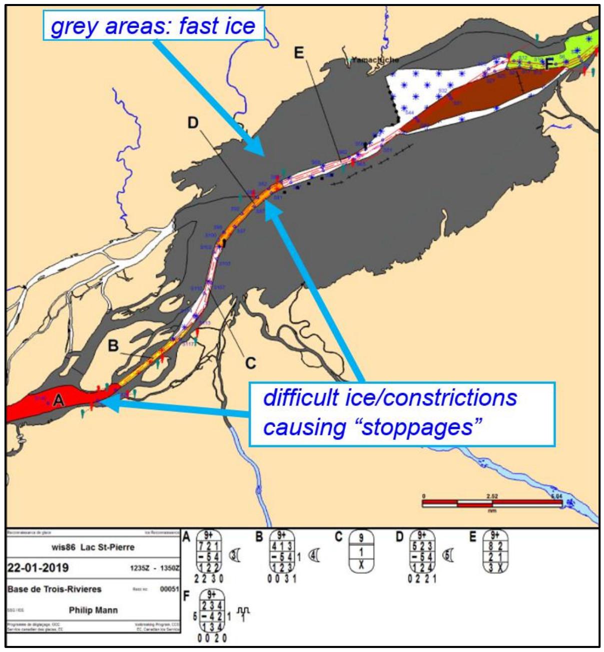

Figure 3. Example of a river ice reconnaissance chart produced by Canadian Ice Service (ECCC) for Lac St-Pierre downstream from Montreal, January 2019. Annotations in blue were added by NRC.

3. Methodologies and available data for assessing ice thickness trends

Several approaches can be used to help assess seasonal variation of ice and historical or future trends. These include

- on-ice measurements, which give information at point locations on the actual historical thickness of fast ice,
- relatively simple freezing degree day calculations, which predict maximum annual ice thickness using air temperature as an input,
- stand-alone thermodynamic models for fast ice, which give detailed predictions of ice thickness growth and decay within a season,
- larger ice-ocean-atmosphere coupled climate models, which can predict ice thickness (as well as air temperatures and numerous other variables) using various algorithms, interdependencies and arrays of input data, and
- analysis of ice observation charts, which are produced regularly during the shipping season and characterize both landfast and mobile ice (via maps of ice thickness categories or ranges).

Freezing degree day methods, thermodynamic models, and larger climate models can all be used to hindcast historical conditions (also known as a ‘reanalysis’), or to attempt to predict future trends. Future trends are generated with the assumption of a given climate warming scenario, so uncertainty is inherent. The present study focusses on *freezing degree day calculations* to examine long-term trends in fast ice. The results are compared with direct *on-ice measurements*. Some preliminary comparisons are also made with *modelled ice thicknesses* from thermodynamic and climate models. As collaborators on this project, McGill University (henceforth referred to as “McGill”) ran a climate model, with a nested thermodynamic model, which provided data to be used in this project. NRC also ran its own thermodynamic model. On-ice measurements were assessed to ground truth or validate the various methods of hindcasting historical ice thicknesses.

Due to time constraints, historical trends in the mobile sea ice will not be assessed in this project. Examination of archived ice charts from ECCC's Canadian Ice Service could be used for this assessment at a later date, if required.

Eleven sites, from Montreal to the Eastern edge of the Gulf, have been selected for examination of trends in maximum annual ice thickness. Three 20-year time periods have been identified for analysis:

- 1990 to 2009, a period for which ice thickness predictions can be compared with actual on-ice thickness measurements,
- 2041 to 2060, and
- 2080 to 2099.

3.1. Locations of analysis sites and historical ice thickness measurements

For the present project, the eleven sites chosen for analysis of both historical and future trends are those for which systematic on-ice thickness measurements have been made by Environment and Climate Change Canada (ECCC). These locations and their Letter-Number designations are shown in Figure 4, with approximate coordinates listed in Table 1. Measurements are taken at approximately the same location every year on a weekly basis, starting after freeze-up when the ice is safe to walk on, and continuing until break-up or when the ice becomes unsafe. The location is selected close to shore, but over a depth of water which will exceed the maximum ice thickness. Air temperature measurements are also generally available from meteorological stations near each ice measurement site. The Ice Thickness Program Collection data are available from the ECCC Data Catalogue (Environment and Climate Change Canada, 2021).

Sites A1, A2, A3 and A7 are all in the vicinity of Montreal harbour, with A1, A2 and A3 very close together on the ship canal at the entrance to the St. Lawrence Seaway. A7 is in the La Prairie Basin, just upstream of the harbour. Further upstream, in Lac St-Louis is D4. Downstream from Montreal are P7 and P11 in Lac St-Pierre. There are two sites in the Saguenay Fjord, P23 and P25. All these sites are in fresh water. Finally, there are two sites in sea water, S35 (Gros Cocouna) on the south side of the Gulf opposite the entrance to the Saguenay Fjord and Havre St Pierre (HSP) further into the Gulf on the North Shore.

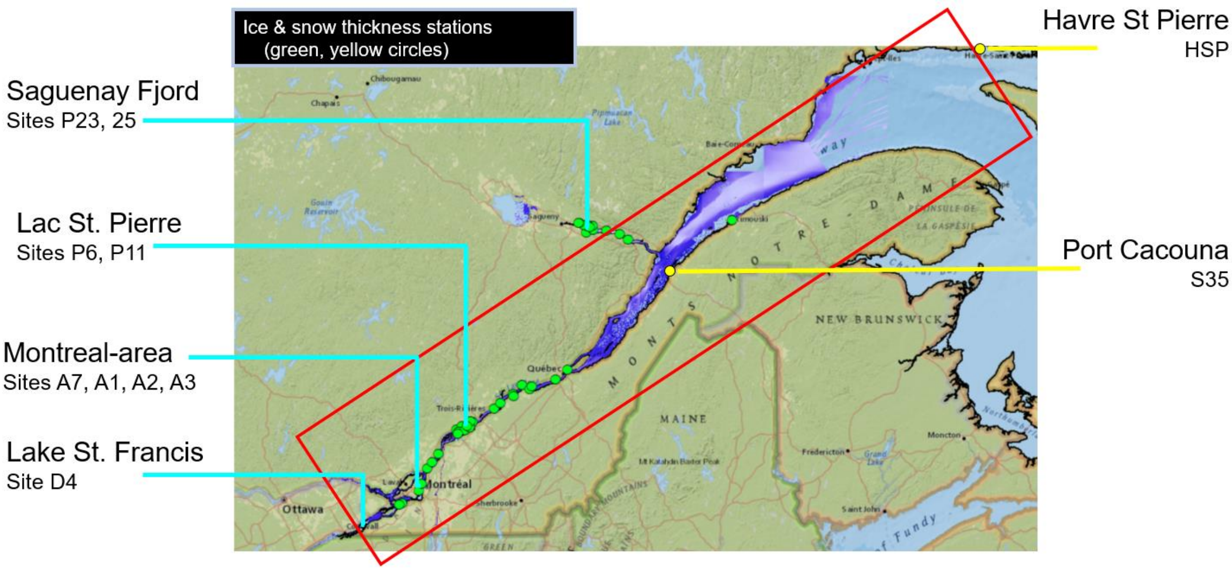

Figure 4. Sites for assessment of historical ice conditions and future trends

Table 1. Approximate locations for ECCC Ice Thickness Program Collection data used in this project

Site	Latitude	Longitude	Name
A1	45.555	73.527 W	Montreal
A2	45.482	73.53 W	Montreal
A3	45.5019	73.5224 W	Montreal
A7	45.41	73.57 W	Montreal
D4	45.13	74.45 W	Cornwall
HSP	50.18	63.581 W	Havre St-Pierre
P11	46.22	72.73 W	Lac St. Pierre
P23	48.345	70.862 W	Bagotville/LaBaie
P25	48.37	70.54 W	Bagotville/LaBaie
P6	46.2	72.95 W	Lac St. Pierre
S35	47.957	69.512 W	Port Cacouna

3.2. Cumulative freezing degree day method for ice thickness prediction

The freezing degree day method is a simple approach to estimating the maximum ice thickness in a winter season. The equation takes the square root of the cumulative freezing degree days (CFDDs) and multiplies it by a site-specific constant. It allows for comparison of ice thicknesses obtained from past air temperatures (whether measured or hindcasted) with thicknesses calculated from future air temperatures (projected from climate simulations). In terms of this project, the greatest caveat of the CFDD approach is that it is heavily weighted towards historical ice conditions, which means one must use care in applying it for future scenarios in a changing climate. Also, the CFDD method cannot be used to predict thickness of the dynamic pack ice, as that ice is more complex in terms of growth and deformation history. Despite these limitations, the CFDD approach is a common and useful way of estimating thicknesses of fast ice and has been used in various forms for at least 130 years. As stated by USACE (2002), to go beyond this standard model would require extensive data collection. The first published version may have been by Stefan (1889). Refinements were made by Michel (1971) and Ashton (1980), to account for snow cover and other factors which inhibit ice growth. Frederking (2018) expands on equations that include CFDDs for the prediction of ice thickness growth.

For the present work, we apply the CFDD equation from USACE (2002). Ice thickness, h (in cm), is defined by

$$h = \alpha \, |CFDD|^{0.5} \qquad \text{Eq. (1)}$$

where,

> CFDD is the cumulative freezing degree days (days with temperature above water's freezing point), in °C-days;
> the empirical coefficient α is a positive number meant to account for site-specific conditions that affect ice growth.

CFDD is calculated by summing each daily mean air temperature that is less than the freezing point of water, i.e., 0°C for fresh water and -1.8°C for sea water. For the purpose of this study the ice growth season is defined as November 1 to March 31. Any days for which mean daily air temperature is above the freezing point are ignored in the summation.

The empirically-derived coefficient α takes into account a number of site-specific parameters that will inhibit ice growth, such as insulating snow cover, sheltered sites, or rapidly-moving water. The value chosen should reflect local conditions so can be different from site to site, and even from year to year. Michel (1971) determined α values for practical application in the conditions described below. The values, converted to metric by USACE (2002) for use in Eqn. 1, are as follows:

- Windy lake with no snow: 2.7
- Average lake with snow: 1.7–2.4
- Average river with snow: 1.4–1.7
- Sheltered small river: 0.7–1.4

In this study, for simplicity, a constant α value of 1.76 was applied for all years and sites. The values could be refined by comparing with ice and snow thickness measurements (where available) and attempting to find a better fit for each site. This step was not done for the present report.

An example for the 1989-1990 winter season at site A1 is presented in Figure 5. Note that the value of the cumulative freezing degree days does not increase wherever the air temperature is above freezing. In that winter the CFDD value is -905 °C-days, which, when substituted into Eq. (1), yields a maximum annual ice thickness of 0.53 m. This figure gives the CFDD based on air temperatures from modelled air temperature data, but actual air temperature measurements may also be used. For the present project we relied mainly on modelled air temperature data, as this allows for a full record of values to use. Frequently, ECCC measurements have large gaps in the record, necessitating a search for data from more distant stations to fill in the blanks.

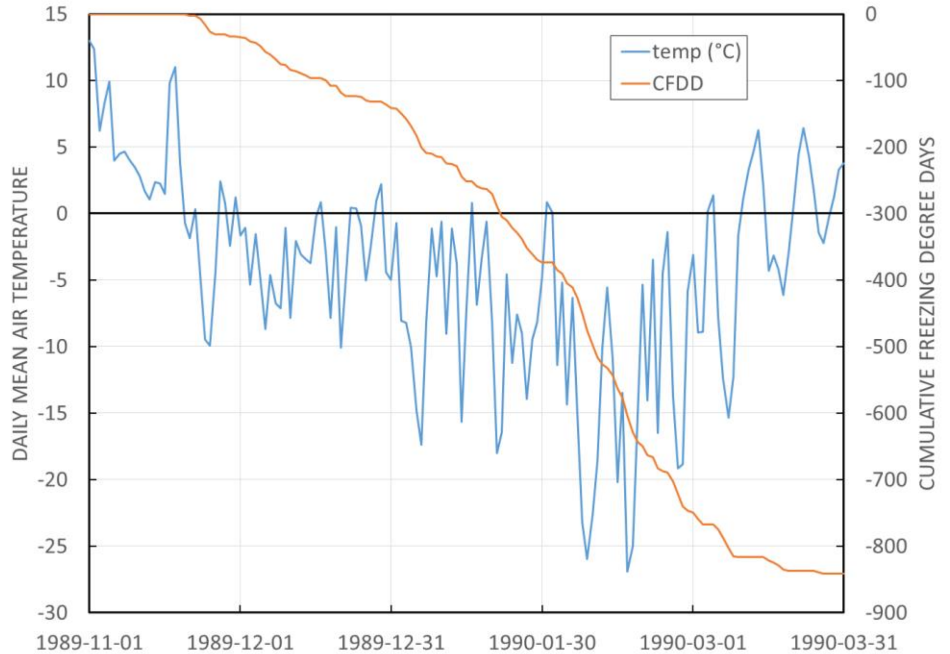

Figure 5. Daily mean air temperature (temp) and Cumulative Freezing Degree Days (CFDD) at site A1 in the Montreal region, based on modelled (reanalysis) air temperatures.

3.3. Climate model predictions for historical and future periods

Many large coupled ice-ocean-atmosphere models have been developed with the capability to provide predictions of predict future ice thicknesses and/or air temperatures based on expected carbon emissions or climate change scenarios. Davy and Outten (2020) give an overview of the sea ice predictions of a number of models used in the Coupled Model Intercomparison Project (CMIP). One of those models is CanESM2. The second generation Canadian Earth System Model, or CanESM2, is a coupled global climate model developed by the Canadian Centre for Climate Modelling and Analysis (CCCma) of ECCC. (For more information, see https://climate-scenarios.canada.ca/?page=canesm2-predictor-notes.) The outputs of climate models are highly dependent on the emissions scenario chosen to run those models (i.e. levels of human-generated greenhouse gas emissions, which cause climate warming). The various emissions scenarios are referred to as Representative Concentration Pathways, or RCPs.

Climate model predictions for ice thickness were not used directly in this project, as their resolution is too coarse over the relatively small waterways of interest. For this reason, NRC collaborated with McGill to obtain finer-resolution climate model prediction data. McGill ran a regional climate model (RCM) that is based on and has the same dynamics as the global environmental multiscale (GEM) model (Côté et al., 1998). Some of the McGill group's previous modelling work is discussed in Jeong and Sushama (2018).

McGill's work for the present project involved implementing the GEM model on a 4-km grid and resampling data from the CanESM2 model to provide temperature data at the resolution needed. For the present report, data corresponding to the RCP8.5 scenario were used. This corresponds to a worst-case, or warmest scenario (see Section 4.2). Air temperature is modelled at 2 m elevation, and the data are provided as a number of layers, including temperature over ground, over a lake, over the sea, and aggregate or average values over the grid cell. For the present work, the aggregate values were selected. These temperature data were then used in the CFDD ice thickness calculations described in Section 4.1 to produce records of historical and future maximum annual ice thickness.

The following important guidance is provided on the data download site for CanESM2 (Canadian Centre for Climate Modelling and Analysis, 2019) and applies to climate model outputs in general:

- Gridded model values are not directly comparable to measured data (weather stations or on-ice measurements). Climate models attempt to represent the full climate system from first principles on large scales. Physical parameterizations are used to approximate the effects of small scale processes.
- Caution is therefore needed when comparing climate model output with observations or analyses on spatial scales shorter than several grid lengths (hundreds of km), or when using model output to study the impacts of climate variability and change.
- Estimates of climate variability and change obtained from climate model results are subject to sampling variability. This uncertainty arises from the natural variability that is part of the observed climate system and is generally well simulated by the climate models.

3.4. Thermodynamic ice growth models

Examination of thermodynamic model results is important in the assessment of intra-annual (i.e., within one year) variation of ice thickness. This can also be used for validation of the other methods of ice thickness prediction. Two thermodynamic models were tested for this project:

- the "NRC model" which was developed by NRC based upon work by Semtner (1976) and is run at NRC, and
- the "McGill FLake model" which has been adapted from a freshwater lake ice model called FLake (Mironov, 2008) and is run at McGill.

Semtner's (1976) model for thermodynamic growth of sea ice is used as a component in various other sea ice forecasting models or systems. NRC's adaptation consists of a vertical 1D heat flux model that is driven by 4 input arrays to describe the daily heat budget (longwave (LW), shortwave (SW), sensible and latent heat fluxes), in addition to input arrays for the snowfall rate, snow/ice surface albedo (reflectivity), and river heat flux. The NRC model was developed for Arctic sea ice, but this project has shown that it can also be applied to river ice and sea ice in more temperate regions. Adapting and applying NRC's thermodynamic model to the St. Lawrence region required considerable effort. The model code has been altered to accept heat budget arrays on a daily basis, rather than the monthly average values used for the Arctic. That essential change was needed to capture daily fluctuations in the input arrays that are so characteristic of winter in temperate regions, compared to the more stable conditions in the Arctic.

McGill's downscaled GEM/ERA5 data (4 km resolution) were used to drive NRC's thermodynamic model. The task required selecting and validating McGill's four heat budget terms (SW, LW, sensible and latent heat), along with 24 other parameters required to drive the model. Two of McGill's heat budget terms (LW, SW) were valid for driving NRC's thermodynamic model; two were not (sensible, latent heat terms). The problem with the latter two terms is believed to be related to the limitations of McGill's implementation of the FLake thermodynamic model. McGill modelled only snow-free ice which seems to have caused FLake to produce (1) overestimated ice thicknesses and (2) inappropriate sensible and latent heat budgets. In reality, snow-free ice infrequently occurs in temperate regions. Bare patches of ice do exist on lakes and rivers, but not usually on fast ice – typically, that is where snow collects. Therefore, NRC used known equations to calculate daily arrays of sensible and latent heats. This step required selecting appropriate constants for the equations, along with making several informed assumptions. To obtain a record of snow depths on ice, NRC applied adjustment factors to McGill's downscaled snow depths over land, based upon snow depths that had been measured on the ice (made by ECCC as part of on-ice measurements; see Section 3.1) and/or at the closest ECCC weather station.

4. Preliminary assessment of historical and future fast ice thickness

4.1. Preliminary analysis of ice thickness based on CFDD and modelled air temperature data

Preliminary values of maximum annual ice thickness for future time periods were calculated using the CFDD method described in Section 3.2, using as input the modelled air temperature data described in Section 3.3. The final values of temperature data chosen for CFDD calculations may be different than those used here, as further work has been done to select the most appropriate data layer for each site (i.e., value over ground, lake or the sea). Therefore, the analysis results will be different at the conclusion of this project in 2023.

CFDD calculations were done for all 11 sites for each of three time periods. An example plot for site A1 is given in Figure 6. For this site the average maximum annual ice thickness decreases from 0.45 m in 2000 to about 0.15 m in 2100, a 66% reduction. Plots for all 11 sites are given in Appendix A and similar trends of decreasing ice thickness were seen at all sites. **Note that refinements to our methodology are presently being made, and the final values will be presented in a second report by March 2023.**

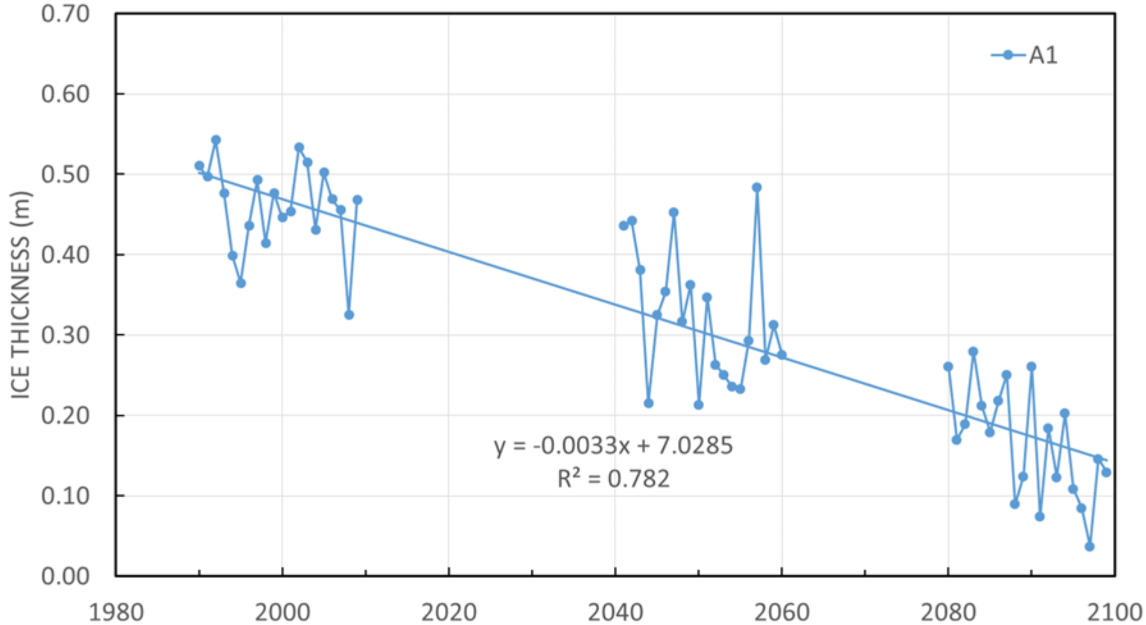

Figure 6. Preliminary analysis of maximum annual ice thickness at site A1 in Montreal area for the three time periods of interest. Values are calculated with the CFDD method using modelled (reanalysis) air temperatures.

While the plots show a consistent trend of decreasing maximum annual ice thickness, tabulated values of maximum annual ice thickness show that there is an *increase in relative variability* for future predictions. Table 2 illustrates this well. The mean value of ice thickness successively decreases for future time periods, but the standard deviation stays roughly the same, with a resulting substantial increase in the coefficient of variation (CV), which is the ratio of standard deviation to the mean of the dataset. CV increases from 0.12 for the historical time period to 0.42 for the period 2080-2099. Appendix B gives the preliminary results for all 11 sites.

Table 2. Preliminary results for maximum annual ice thickness at site A1 (Montreal area) for three periods, based on CFDD method with modelled (reanalysis) temperature data

Year	Thickness (m)	Year	Thickness (m)	Year	Thickness (m)
1990	0.51	2041	0.44	2080	0.26
1991	0.50	2042	0.44	2081	0.17
1992	0.54	2043	0.38	2082	0.19
1993	0.48	2044	0.21	2083	0.28
1994	0.40	2045	0.33	2084	0.21
1995	0.37	2046	0.35	2085	0.18
1996	0.44	2047	0.45	2086	0.22
1997	0.49	2048	0.32	2087	0.25
1998	0.41	2049	0.36	2088	0.09
1999	0.48	2050	0.21	2089	0.12
2000	0.45	2051	0.35	2090	0.26
2001	0.45	2052	0.26	2091	0.07
2002	0.53	2053	0.25	2092	0.18
2003	0.52	2054	0.24	2093	0.12
2004	0.43	2055	0.23	2094	0.20
2005	0.50	2056	0.29	2095	0.11
2006	0.47	2057	0.48	2096	0.08
2007	0.46	2058	0.27	2097	0.04
2008	0.33	2059	0.31	2098	0.15
2009	0.47	2060	0.28	2099	0.13
Average	*0.46*		*0.32*		*0.17*
Standard dev.	*0.05*		*0.08*		*0.07*
CV	*0.12*		*0.26*		*0.42*

4.2. Comparison of historical predictions with on-ice measurements and modelled data

The results presented so far have been predictions of ice thickness based a CFDD calculation using mean modelled daily air temperatures. As a way of verifying these thickness estimates, they may be compared to

- Actual on-ice measurements (if available)
- CFDD calculations using air temperature measured at a nearby site (if available)
- Climate model predictions for dates in the past.

To give an indication of the accuracy of the predictions, they may be compared with historical on-ice thickness measurements made periodically throughout the winter (see Section 3.1). Unfortunately the ice measurement program mostly ended around the year 2000, with the last measurements being taken at site S35 in 2009. Additionally, measurements at most sites had gaps for some years – so generally less than half of our period of interest is covered. The maximum annual ice thicknesses were extracted from the available measurements, and compared with the cumulative freezing degree day based predictions. An example for site A1 is given in Figure 7. The preliminary plots for all 11 sites are presented in the plots in Appendix C.

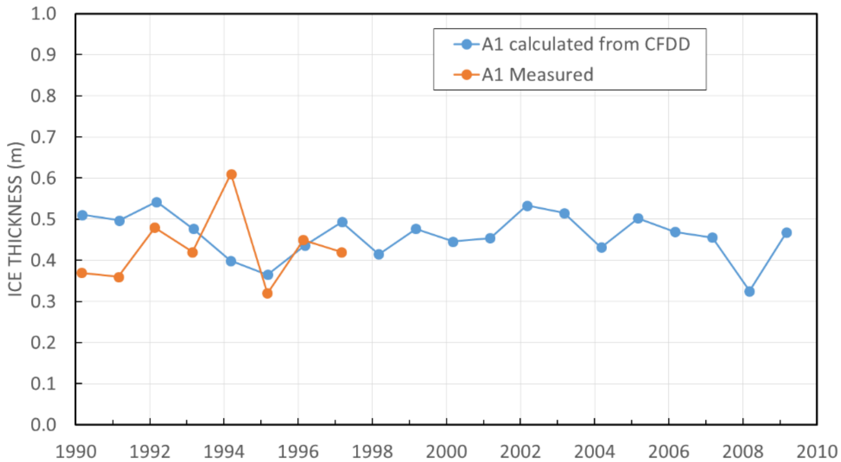

Figure 7. Preliminary analysis of maximum annual ice thickness at Site A1, in Montreal area, calculated using CFDD (based on modelled/reanalysis air temperature), compared with actual on-ice measurements made by ECCC.

Table 3 presents a comparison of all 11 sites. Comparisons between measured and calculated ice thicknesses are made based on the years for which measured data are available, which ranged from 5 to 18 years. Note that the calculated ice thicknesses for sites A2 and A3 are identical, as the sites are so close that they fall within the same model grid cell. Correlation coefficients were calculated for the annual maximum on-ice thickness measurements and corresponding CFDD calculation at each site. As seen in the table, correlation is low (perfect correlation would be indicated by a coefficient = 1). Due to the small sample size, correlation analysis is of little value. Averages of the maximum ice thickness were calculated at each site, for years for which on-ice measurements were available. The CFDD thicknesses ranged from 38% less than to 15% more than the on-ice measurements, showing that the calculations are at least in the same range as on-ice measurements.

Table 3. Preliminary comparison of maximum annual ice thickness, averaged over 1990-2009. Measured thicknesses are from the ECCC on-ice measurement program. CFDD calculations of ice thickness used modelled air temperatures as input. Basic analysis is presented to compare the CFDD calculations with available on-ice thickness measurements. Data gaps exist in the measurement record, and analysis is done based only on years with measured data.

	Site										
	A1	**A2**	**A3**	**A7**	**D4**	**P6**	**P11**	**P23**	**P25**	**S35***	**HSP**
Number of years between 1990 and 2009 with ice thickness measurements	8	7	10	10	8	11	12	10	13	18	5
ECCC on-ice thickness measurement (m) – average	0.47	0.44	0.44	0.42	0.39	0.43	0.43	0.56	0.57	0.36	0.47
CFDD method calculated ice thickness (m) – average	0.43	0.39	0.38	0.54	0.44	0.54	0.61	0.67	0.77	0.58	0.57
Ratio of thickness calculated/measured	1.08	1.14	1.15	0.77	0.89	0.79	0.70	0.85	0.74	0.62	0.84
Correlation coefficient	-0.08	-0.09	0.37	0.24	0.24	-0.08	0.10	-0.09	-0.14	0.27	0.56

In order to give more context for a longer time period, the maximum annual ice thickness was assessed using four methods explained in previous sections of this report:

- on-ice thickness measurements made by ECCC (see Section 3.1)
- CFDD calculations based on measured air temperature at the nearby Montreal weather station (see Section 3.2)
- CFDD calculations based on McGill's modelled air temperature (see Sections 3.2 and 3.3)
- McGill's climate modelling of ice thickness (see Section 3.3)

The results for site A1 are presented in Figure 8. There is a wide "band" of variability from year to year. Preliminary analysis (not shown on the plot) indicates that each of the 4 sets of thickness data trend downwards with time, indicating a thinning of ice from 1970 to 2020. This preliminary analysis was performed as an example only for one site; further examination of data for this and the other sites will be performed, along with statistical analysis, in 2022-23.

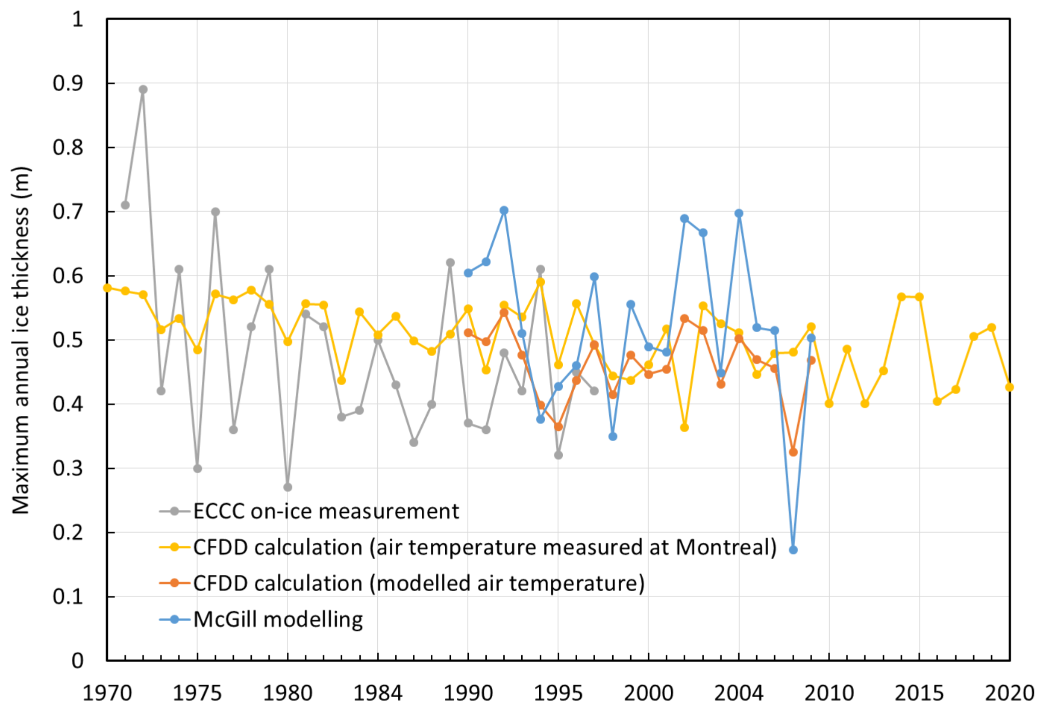

Figure 8. Comparison of four methods for assessing ice thickness at Site A1, Montreal area: ECCC on-ice measurements; CFDD method with (a) the measured air temperature at the nearby Montreal station and (b) the McGill-modelled air temperature; and McGill's modelling of ice thickness from their climate model.

4.3. Uncertainties in assessing fast ice thickness

Uncertainties are inherent in any calculated, modelled or measured data. Some of the expected uncertainties for the data and methods used in the present project are:

- Uncertainty in the CFDD method used for both historical and future ice thickness estimation. The site-specific constant (alpha) was not adjusted per site. Doing so would result in a better fit to historical data. The CFDD formula is based on historical data, and the only variable that is considered for future predictions is air temperature. The waterways will heat in the future as well, and snow depth patterns may change; this is not accounted for in the present work.
- Uncertainty in ECCC ice thickness program measurements. The most recent measurements are from 2010, and measurements ended sooner at many sites. There are gaps in records for many sites. It is possible that ECCC stopped taking measurements before ice reached its peak thickness. Local variations in ice thickness are not accounted for. Site location may change slightly from year to year.
- Accuracy of McGill modelling of air temperature (RCP8.5 scenario), the outputs of which were used in the CFDD analysis of this report. At this time we have not done a full assessment of the accuracy of the historical modelled temperature data for the St. Lawrence Marine Corridor (i.e., comparison to measured temperatures at all sites). Investigations at site P23 showed the modelled air temperature to be warmer in winter than historical measurements. CanESM2 data are used as input to McGill's modelling. Previous analysis, for the *entire Canadian land mass*, has shown CanESM2 temperatures to be in good agreement with observations (Kushner et al., 2018). Further examination of McGill's modelled and interpolated values over the waterways may be useful.
- Uncertainty in the global warming scenario used for prediction of future ice conditions. The climate warming scenario plays a large role in the future annual ice thickness predictions, and the choice of scenario may overshadow any refinements to our methodology for ice thickness estimation. For the present analysis, the high emission scenario RCP8.5 was used. It is expected that warming globally, including for Canada, will be similar under all plausible emission pathways over the next two decades (Bush and Lemmen, 2019) – our coming years are in effect "baked in". However, efforts to reduce greenhouse gas emissions beginning now and continuing into the future will have an increasing impact on the amount of additional warming expected in the future. The low emission scenario requires global emissions to peak almost immediately, with rapid and deep reductions thereafter. As shown in Figure 9, projected temperature increases for Canada by year 2100 range from an increase of about 2°C for the RCP2.6 low emission scenario, to 6°C for the RCP8.5 high emission scenario, compared to the reference period of 1986–2005. In this figure, the thin lines show results from individual models, with the mean represented by the heavy lines.

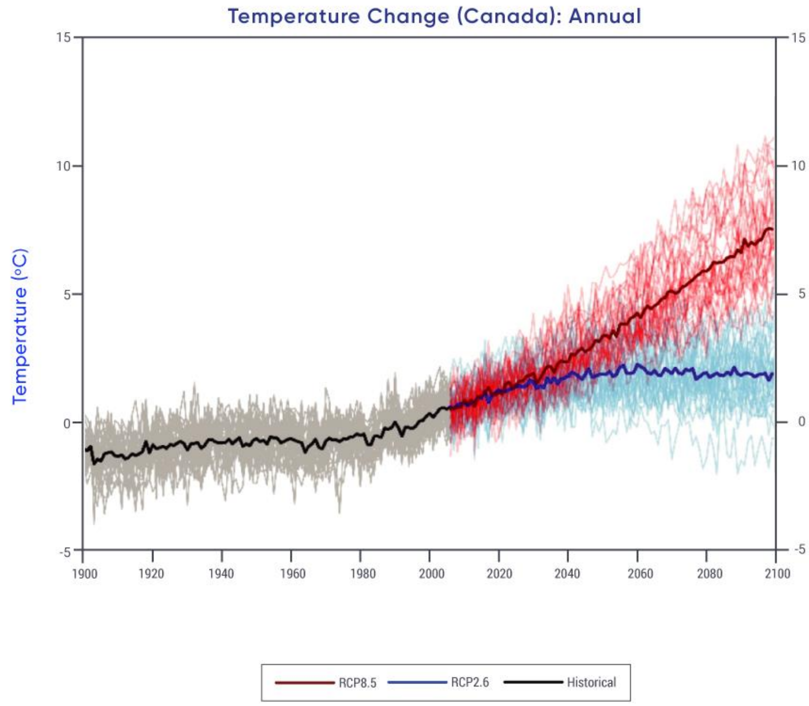

Figure 9. Reproduced from Bush and Lemmen, 2019 (Figure 4.8). Projected Canada-wide annual average temperature change based on low emission scenario RCP2.6 (blue) and high emission scenario RCP8.5 (red), compared to the historical period (black). The high emission scenario was used in the analysis for this report.

5. Fast ice season duration (initial results)

The NRC thermodynamic model (based on Semtner, 1976, and described in Section 3.4) was used to provide time series traces of the fast ice thickness for the 9 river ice sites over the 1989 – 2009 period. The NRC model was driven with downscaled (4 km resolution) GEM/ERA5 data supplied by McGill University. Note that this is a different dataset than the McGill modelling used to generate air temperatures for the CFDD calculations in Section 4.1 (which relied on CanESM2 data and an assumption of RCP8.5 scenario). GEM/ERA5-driven results from NRC's thermodynamic model were compared to (1) ice thickness measurements at 9 locations, (2) ice charts, where available, and (3) the thermodynamic model (FLake) being used by our McGill University collaborators. The sites in the Gulf are not yet assessed.

Data from Environment and Climate Change Canada (ECCC) are critical to validating results from the thermodynamic models and FDD approach for the 1989 – 2009 period. They are also necessary for establishing baselines to evaluate future climate parameters. The ECCC parameters of interest to the NRC thermodynamic model include observed air temperatures, snow depths, snow depth & precipitation rates (rain/snow), and wind speeds. ECCC data were obtained for weather stations in closest proximity to our ice sites, including Cornwall, Trois Rivières, Lac St. Pierre, Rivière du Loup, Bagotville, LaBaie and Havre St. Pierre. Weather records at a given site often have gaps that must be filled by other locations nearby. In addition, since the ECCC weather stations are on land – and land-based snow depths are typically higher than over the ice (Sturm and Liston, 2003) – ECCC's snow depths were adjusted to make them appropriate for snow-over-ice. ECCC's snow depths were compared to the measured on-ice snow depths, where available, to obtain 'snow adjustment factors' for our 11 sites. Adjustment factors varied, depending upon the site and particular year, but typically ranged from 0.10 – 1.0. For example, a snow adjustment factor of 0.25 was most often used for Site P23 (12 years), 0.50 for Site P6 (12 years) and 1.0 for Montreal (19 years). The same adjustment factors should be applied to McGill's downscaled snow depths for future periods when applying NRC's thermodynamic model for those periods. Work on the future periods has not yet started.

The two thermodynamic models (NRC's vs. McGill's FLake model) are compared, and validated with on-ice measurements and ice charts, where possible. Results from Site P23 (Saguenay Fjord) are shown in Figure 10 for two winters: one with minimal snow and the other with substantial snow. During both winters, NRC model thicknesses are in good agreement with measured ice thicknesses. In comparison, the FLake model overestimates the ice thicknesses for both winters. Comparison of ice thickness during the two winters clearly shows the retarding effect that an insulating layer of snow has on ice growth. Notice also that ice charts began being issued after fast ice developed (~November 26) and ceased before the fast ice at Site P23 melted in its entirety (~April 27). That is to be expected: river ice charts are issued to support shipping, not to document the start/end dates of fast ice. However, it aptly illustrates that ice season lengths based upon river ice charts can be shorter than the true season length, depending upon the site of interest.

Figure 11 shows model results vs. measurements for two winters at Site A3, which is located in the canal across from the Port of Montreal. The figure includes a winter with minimal snow cover (1996) and a winter with substantial snow (1993). In both years, results from NRC's model is in good agreement with on-ice measurements whereas the FLake model overestimates ice thicknesses. For this site, however, FLake's over-prediction is not just due to the lack of snow cover. We suspect that additional factors come into play to retard ice growth in downtown Montreal. These factors can be incorporated into the NRC model, but are not easily incorporated into the FLake model. They include any sources of external heat, such as discharge/drainage into the canal where Site A3 is located (as occurs in the Lachine canal, on the other side of the river) and/or atmospheric warming due to commercial and residential activities in the city core (see Oke and East, 1971). Thermal plumes could also play a role on ice conditions in parts of the St. Lawrence River passing through Montreal, as discussed in Dingman et al. (1968).

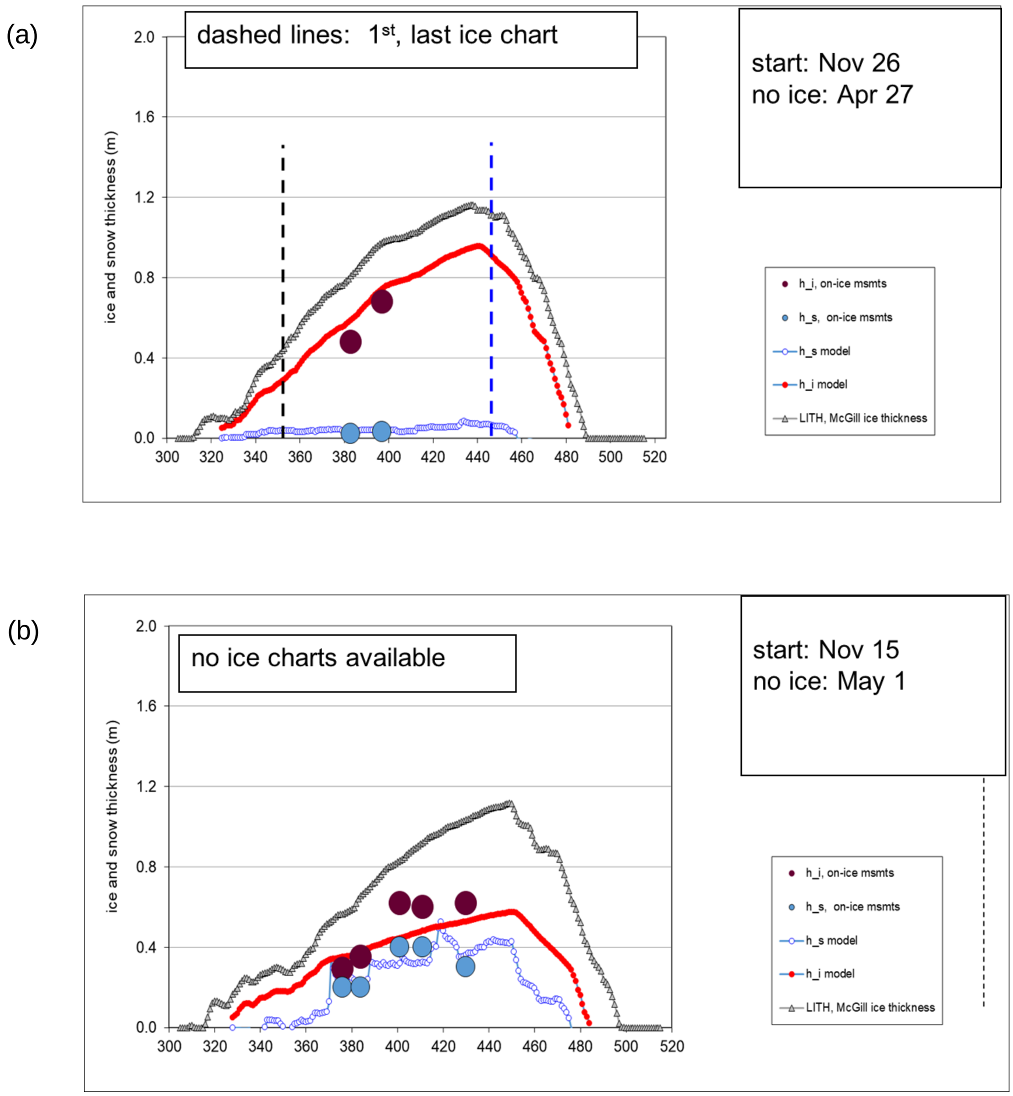

Figure 10. Results for Site P23, Saguenay Fjord for the (a) 2005 winter with minimal snow and (b) 1997 winter with substantial snow. Measurement values are shown for ice thickness (large purple markers) and snow thickness (large blue markers). Predictions are shown from the NRC model (red line) and McGill's FLake model (grey line). Snow thicknesses from the NRC model (blue line) are based upon prescribed values.

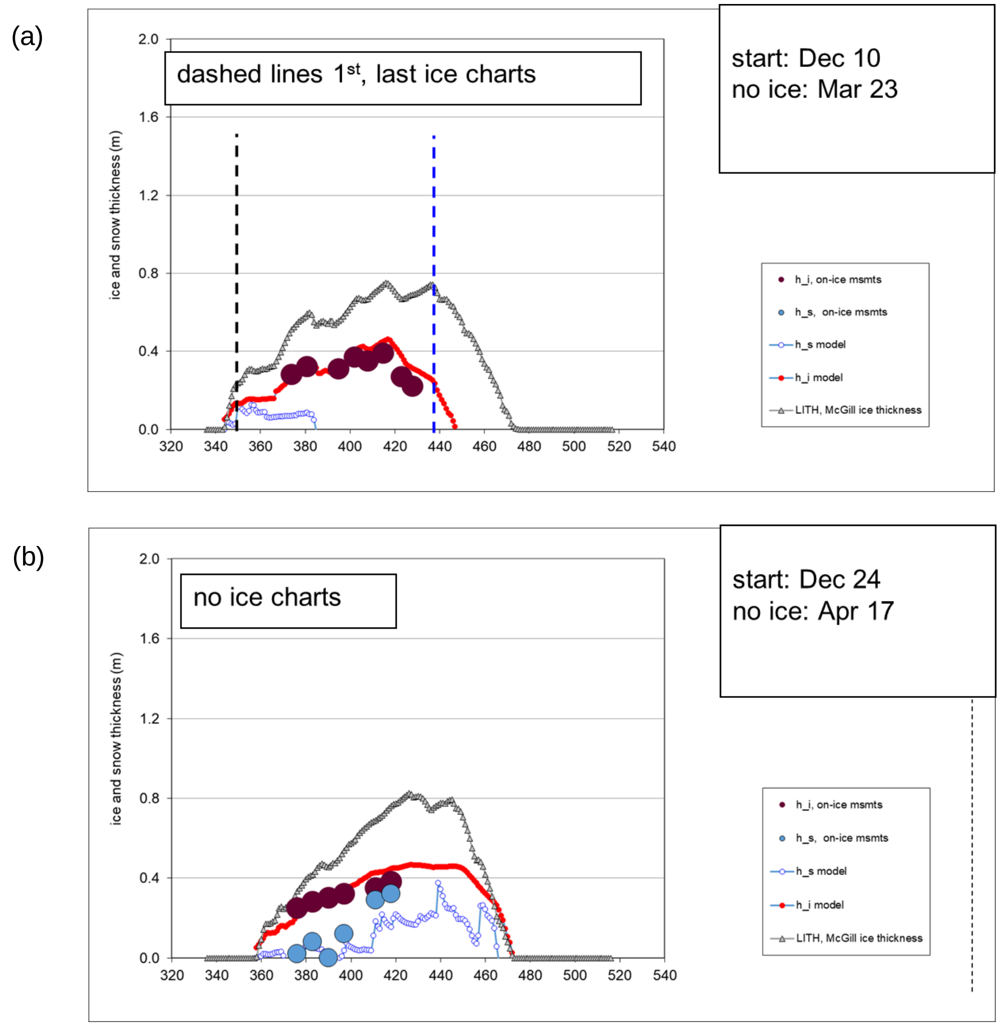

Figure 11. Results for Site A3, downtown Montreal for the (a) 1996 winter with minimal snow and (b) 1993 winter with substantial snow. Measurement values are shown for ice thickness (large purple markers) and snow thickness (large blue markers). Predictions are shown from the NRC model (red line) and McGill's FLake model (grey line). Snow thicknesses from the NRC model (blue line) are based upon prescribed values.

Figure 10 and Figure 11 show results for Site P23 and A3 for two winters each. Results from the NRC thermodynamic model were in equally good agreement with the observed thicknesses for other winters during the 1989 – 2009 period, where we have supporting on-ice measurements. The same can be said of the other 7 river ice sites. Having established the validity of results from the NRC model, we now use the data to examine trendlines. Figure 12 shows trendlines based upon NRC model results for 3 of the river sites examined for period 1. The strongest downward trend in maximum winter ice thickness occurs at Site P23 in Saguenay Fjord. Site P6 in Lac St. Pierre shows a lesser downward trend in thickness, and Site A3 in Montreal shows a stable trend in maximum thickness. The R^2 values for the three trendlines are very low (each less than 0.05). For comparison, maximum ice thicknesses from McGill's FLake model – which are recognized as being conservative – produced similarly low R^2 values (not shown: 0.05 for P23; 0.01 for P6; 0.00 for A3). Such low R^2 values illustrate the large inter-annual variability in ice thicknesses at these three sites – and other sites in the St. Lawrence River (not shown). Note that the trendlines in Figure 12 should be taken as preliminary until tested for statistical significance, and corroborated by data from future scenarios.

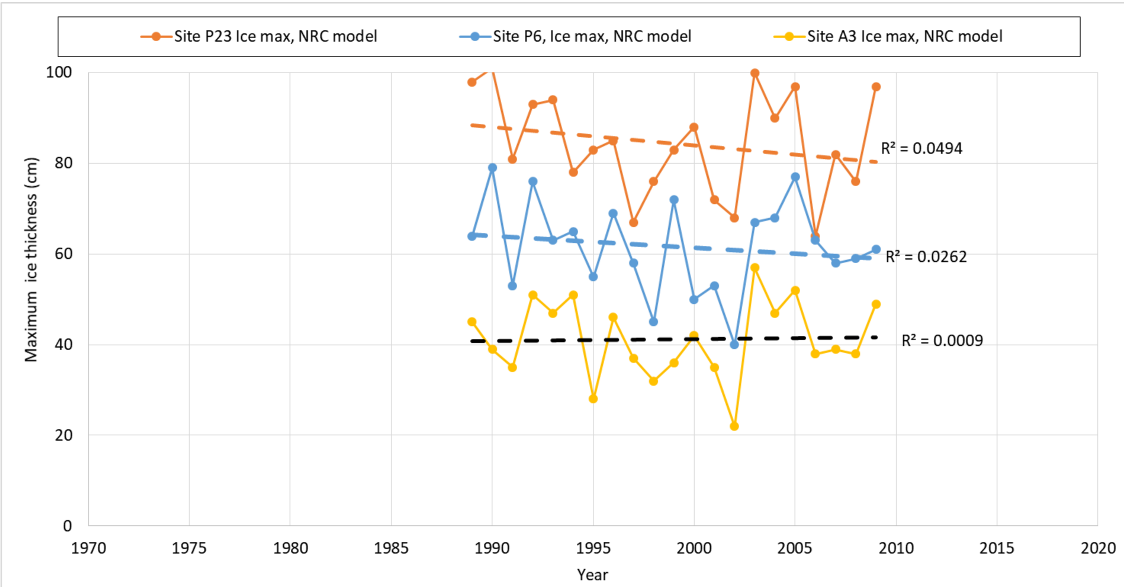

Figure 12. Preliminary assessment of maximum annual ice thickness from the NRC model for three river ice sites: (a) Site P23 in Saguenay Fjord, (b) Site P6 in Lac St. Pierre and (c) Site A3 in downtown Montreal.

6. Considerations for mobile pack ice thickness and season duration

This report has focussed on fast ice, the stationary ice which extends from the shoreline. For some applications, including shipping, it is the mobile pack ice zone that is of more interest. Mobile ice is strongly influenced by winds and currents, which result in ice dynamics and deformation. Assessments of pack ice thickness evolution are therefore more complex than those for fast ice. Trends in fast ice thickness are relevant when considering the mobile ice zone, and it is expected that pack ice thickness will also decrease with increasing air and ocean temperatures. Analysis of the mobile ice zone has not been carried out for the present report.

Neither the CFDD approach nor the thermodynamic modelling can be used to document the thickness of isolated floes and/or broken-ice in areas beyond the landfast ice. Instead, archived ECCC ice chart products for the River and Gulf should be used to quantify ice thicknesses in the regions of mobile pack ice. The analysis should take into consideration the fact that ice charts give ice thickness only as a range of values within a stage of development (e.g., grey-white sea ice: range of 15-30cm; or thick lake ice: range 30-70cm). The interpretation of ice chart thicknesses in shipping channels is also confounded by the dynamics and deformation (ridging, etc.) in mobile pack ice, as well as by icebreaking activity in shipping channels.

Trends in snow and ice thicknesses at the 9 river ice sites and 2 Gulf sites can be used as a proxy for changes beyond the fast ice, but ice charts should be studied to more accurately document historical mobile ice conditions. Trends from the fast ice (using CFDD calculations and thermodynamic modelling) could be used to corroborate trends obtained from ice charts analysis, and extrapolated to future periods. In addition, published results from a model that has been developed by Dept. of Fisheries and Oceans (see Galbraith et al., 2020) could be consulted for the Gulf domain, where appropriate.

Figure 13 gives an indication of the overall percent ice coverage for the Gulf of St. Lawrence region since 1969. Ice conditions are generally less severe in recent years. This plot, produced by ECCC, gives total ice coverage for the entire area shown in the figure's inset image (including St. Lawrence River and Gulf, as well as Nova Scotia and western Newfoundland). Differences in ice coverage in individual regions have not been studied.

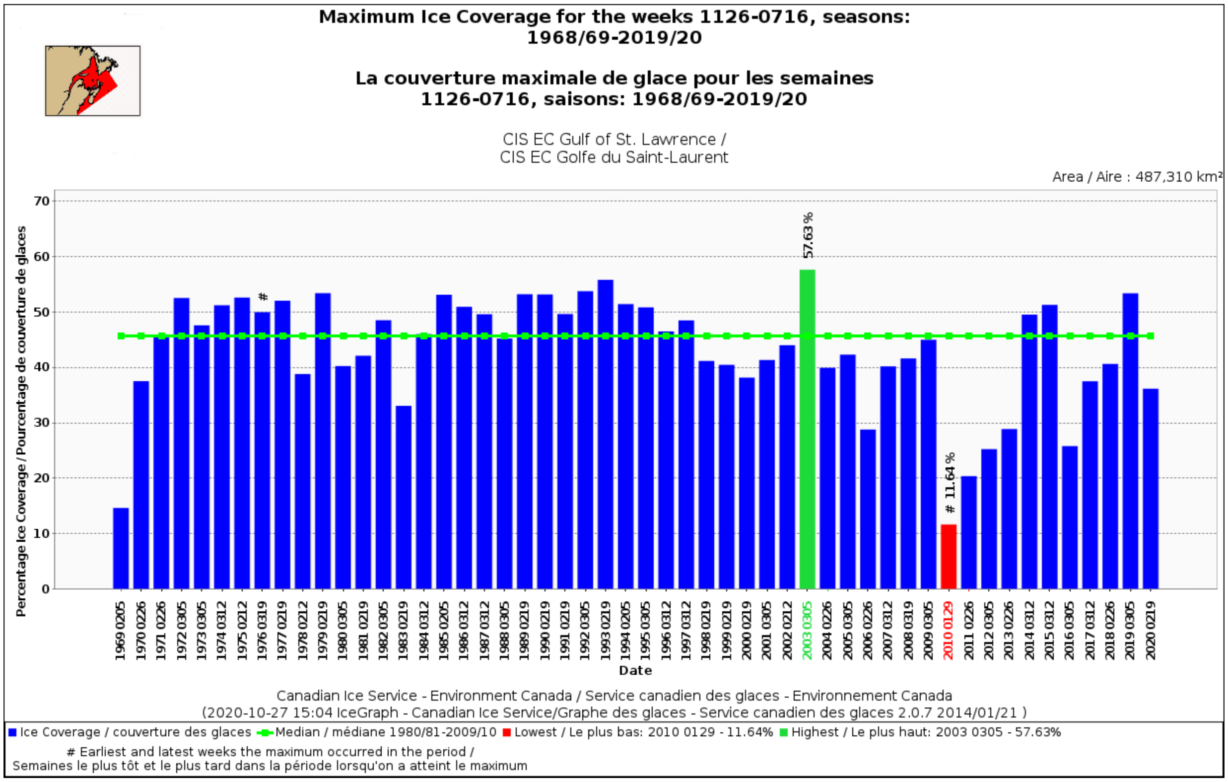

Figure 13. Environment and Climate Change Canada (2020) analysis of maximum annual ice cover, as a percent coverage of the Gulf area shown in red on the inset map.

7. Conclusions and recommendations

Work this year has focussed on a preliminary analysis of maximum annual thickness expected for the fast ice at selected sites along the coast of the St. Lawrence River and Gulf of St. Lawrence. In summary:

- The analysis presented in this report is preliminary. Methodologies are presently being refined and the final assessments of fast ice thicknesses (hindcast as well as future values) will be presented in a second report by March 2023.
- Preliminary assessments of fast ice thickness were made using a cumulative freezing degree day (CFDD) approach. The predictions for 1990 to 2009 were generally in the same range as the available on-ice thickness measurements. The average thickness was calculated at each site; the CFDD method thickness ranged from 38% less than to 15% more than the average measured thickness. The predicted fast ice thicknesses at all sites show a large degree of inter-annual variability; similar variability is also seen in the historical on-ice measurement data.

- Preliminary CFDD calculations generally indicate a *weak trend in decrease of fast ice thickness at all sites between 1990 and 2010* (quantification of decrease and statistical significance were not yet assessed). For this time period, too few years of on-ice measurements exist to generate statistics. Examination of data from one site near Montreal from 1970 to 2020 indicates a general reduction in annual maximum ice thickness.
- Preliminary CFDD calculations based on future air temperature predictions (for RCP8.5, or warmest climate change scenario) indicate a *further reduction in fast ice thickness at all sites between the present time and the year 2100*. Preliminary results indicate that the maximum annual fast ice thickness at the end of this century could (on average) be half, or less, of the thickness values in the early 2000s, for all sites examined. The calculations show an *increase in variability in future ice thickness values*. The CFDD method may not be appropriate for future periods, as it is heavily weighted toward historical conditions. The future predictions of ice growth assume that only the air temperature changes; in reality, the future snow thicknesses and underlying water temperatures (amongst other factors) may also change enough to affect results.
- McGill's climate modelling predictions of future ice thickness could provide another means of examining future ice trends. At the time of this writing, these data were not used in this project as more work is needed to assess the suitability of the methods used (including the thermodynamic model) and validate historical results.
- Uncertainties in data and methodology exist in all the methods of estimating future ice thickness. However, the difference in future temperatures based on either a high or low emission climate change scenario may have a much larger impact on expected ice thickness than any refinements to our methods. For the present work, future air temperatures corresponding to the high emission (worst case) scenario were used. This results in larger decreases in ice thickness.
- To begin to examine ice season duration, some initial thermodynamic modelling was carried out. NRC's thermodynamic model showed good agreement with other methods for historical years. Further testing and refinement is needed for McGill's implementation of the FLake thermodynamic model before those data can be used in this project.

This project continues until the end of March, 2023. The recommendations for 2022-23 include:

- Further assessment of the maximum annual ice thickness should be performed, including refinement of methodologies, statistical analysis, and quantification of uncertainty where possible.
- The CFDD method, if deemed suitable for future periods, should be refined. Site-specific alpha values should be used in Eq. 1 to replace the uniform value assumed in the present study. As the CFDD estimates only consider the effects of changes in temperature, adjustments may also be needed to account for other climate change effects (e.g., warming waterways or less snow).
- For future periods, climate model and/or thermodynamic model outputs should be used to provide improved ice thickness predictions.
- A thermodynamic model should be used to study the predicted ice season duration for future time periods, with validation through comparison of model results to historical on-ice measurements.
- The effect of the climate warming scenario on ice thickness should be tested.
- If future trends are required for the mobile pack ice, historical ice charts should be assessed. Trends from the fast ice (using the CFDD method and thermodynamic modelling) then could be used to corroborate trends obtained from ice chart analysis, and extrapolated to future periods.

8. Acknowledgements

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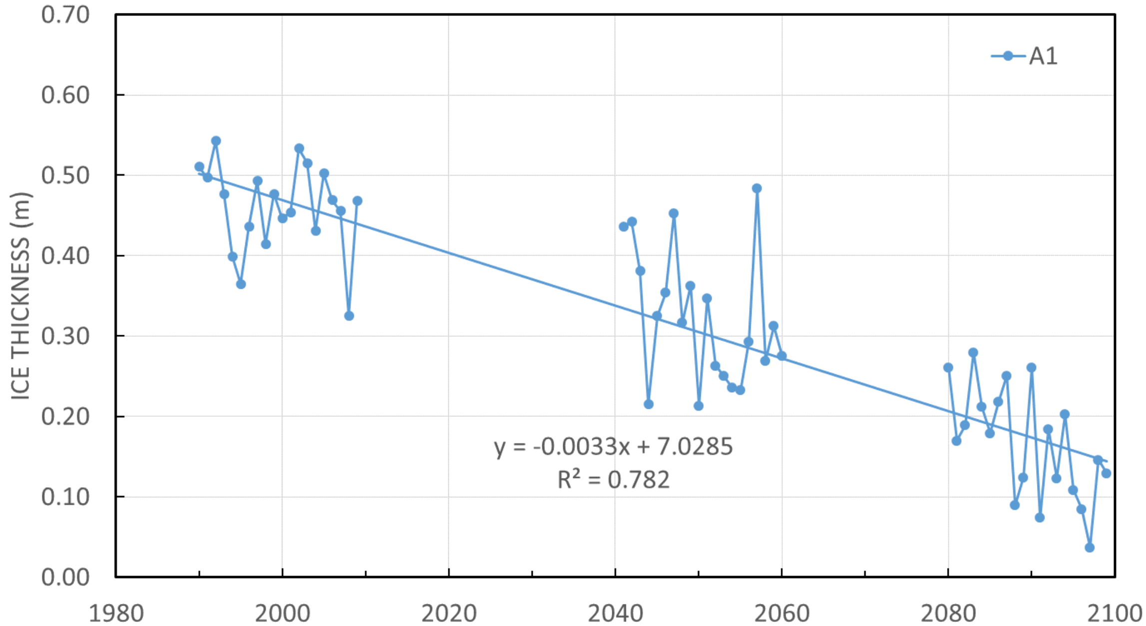
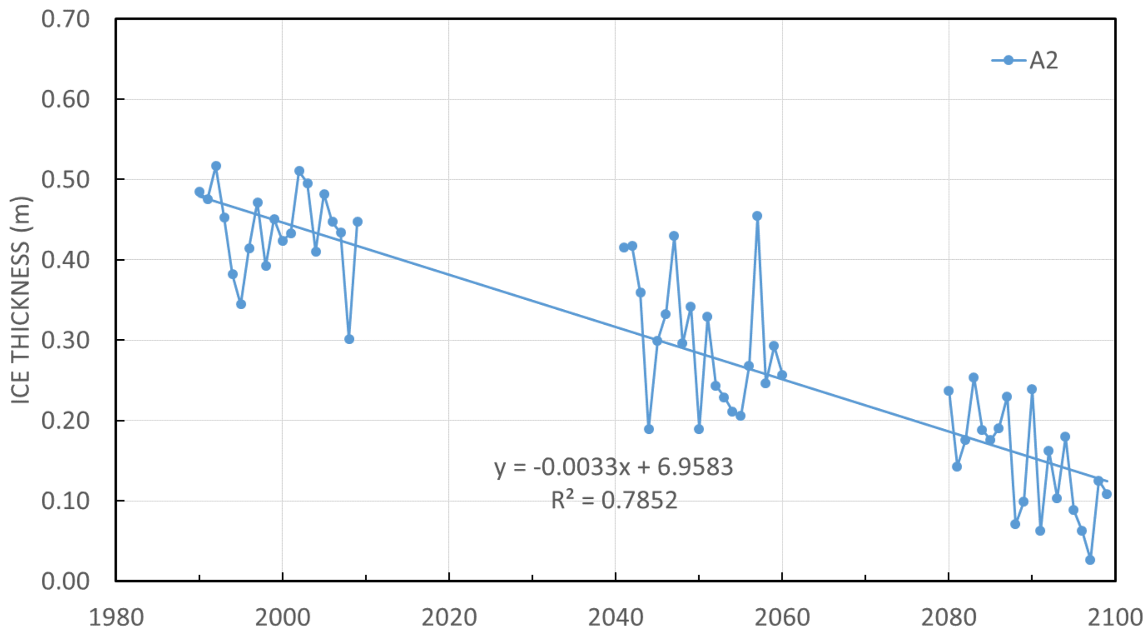
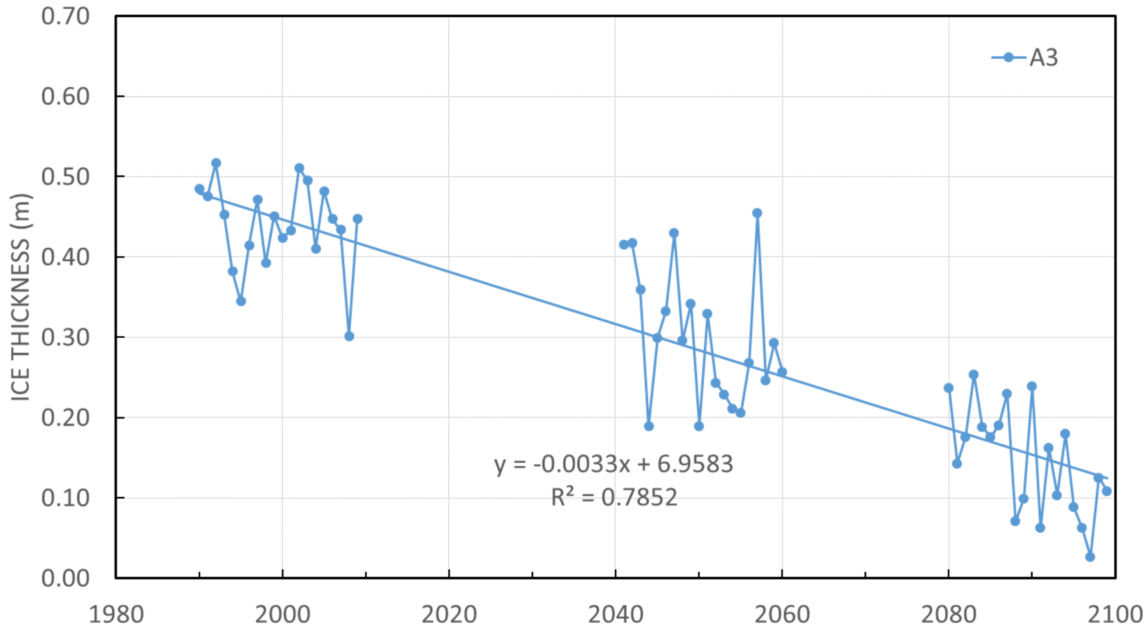
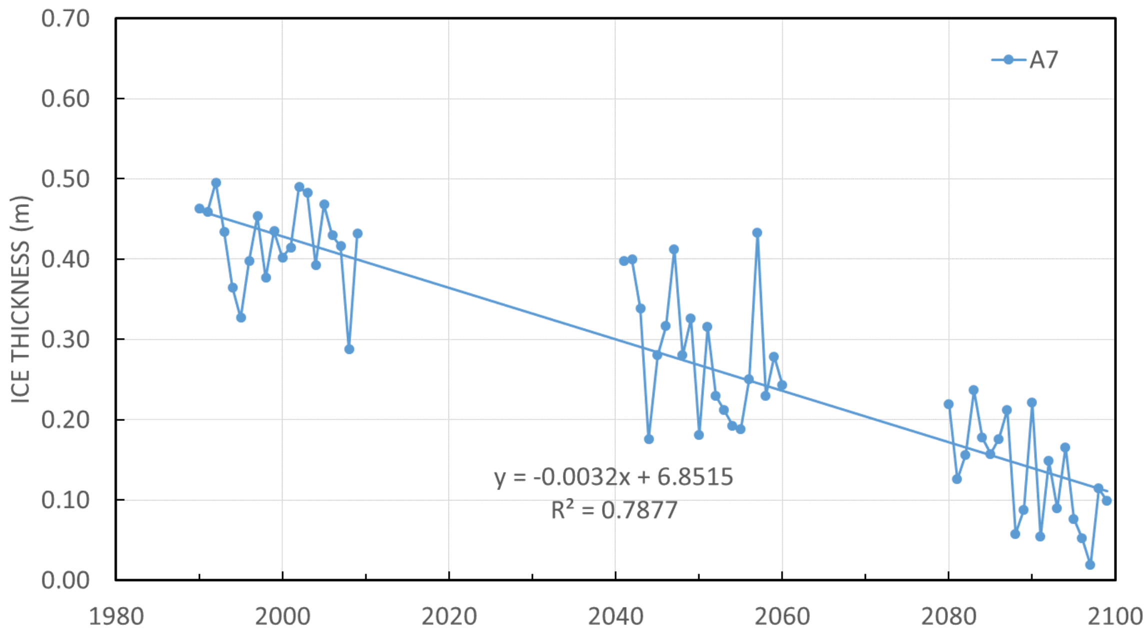
Appendix A: Preliminary plots of maximum annual ice thickness at each site for 1990 - 2100, based on CFDD method with modelled air temperatures

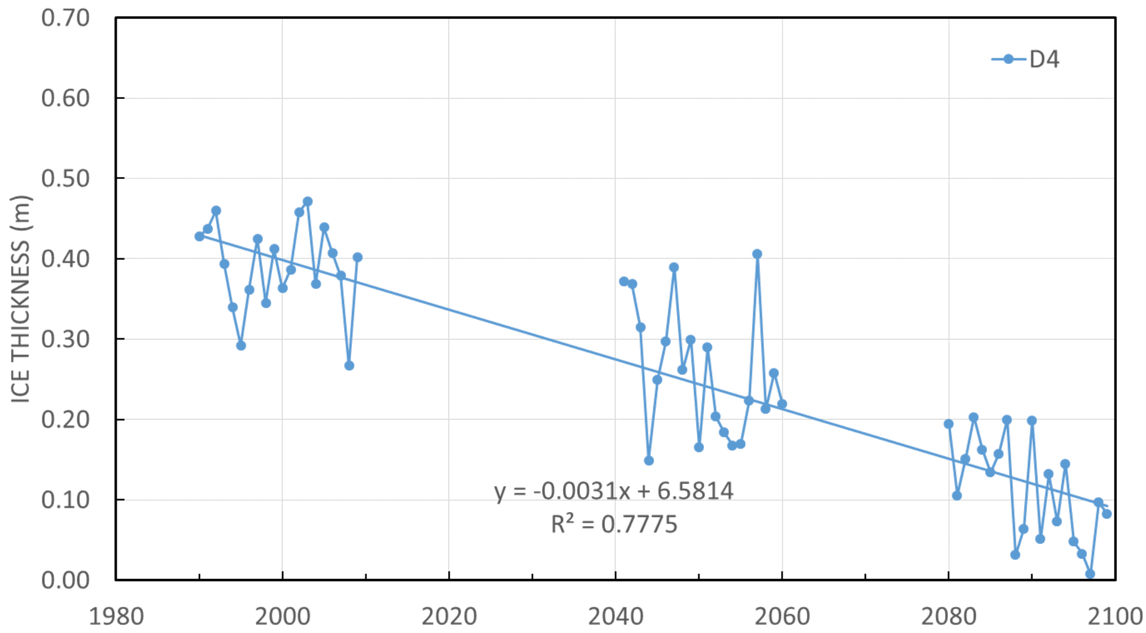
Site name is indicated at top right of each figure

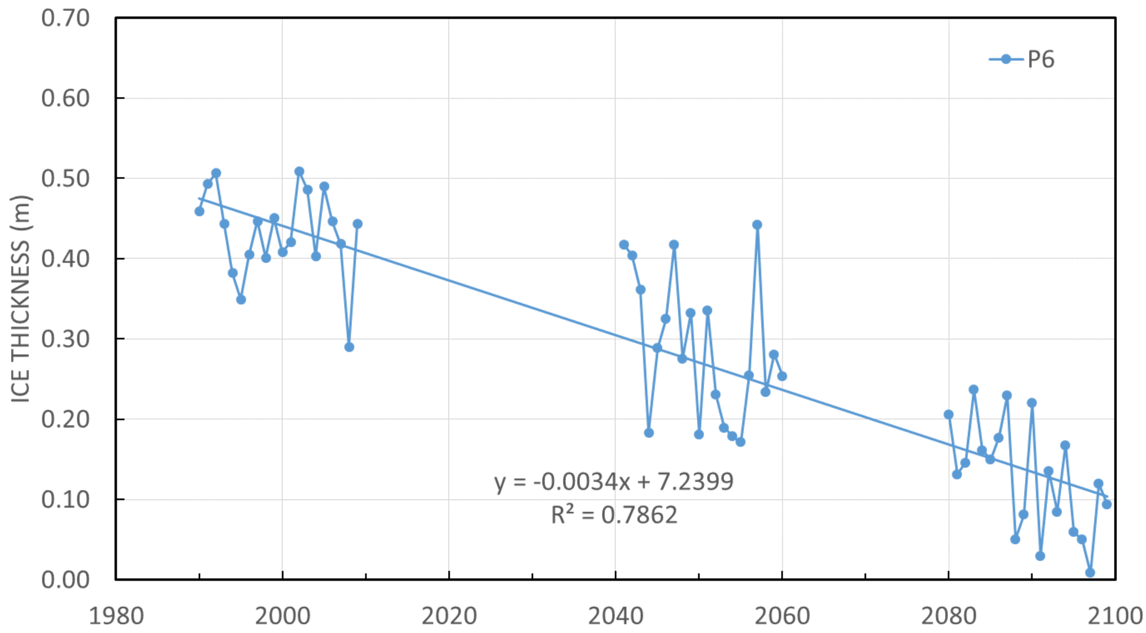


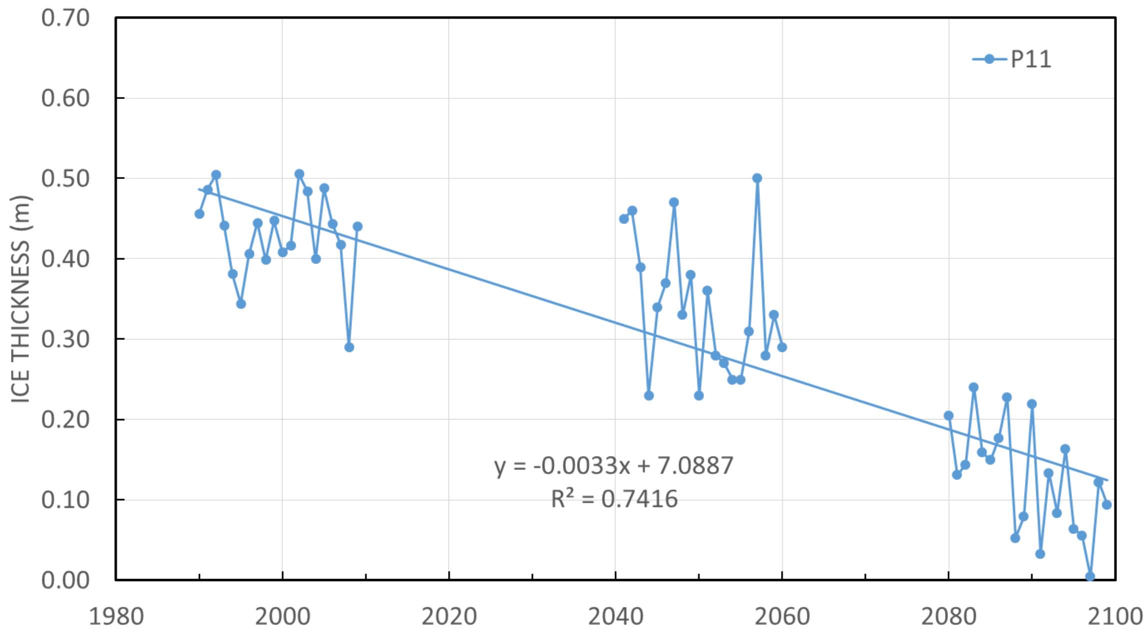



A3
ICE THICKNESS (m)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1980
2000
2020
2040
2060
2080
2100
y = -0.0033x + 6.9583
R² = 0.7852

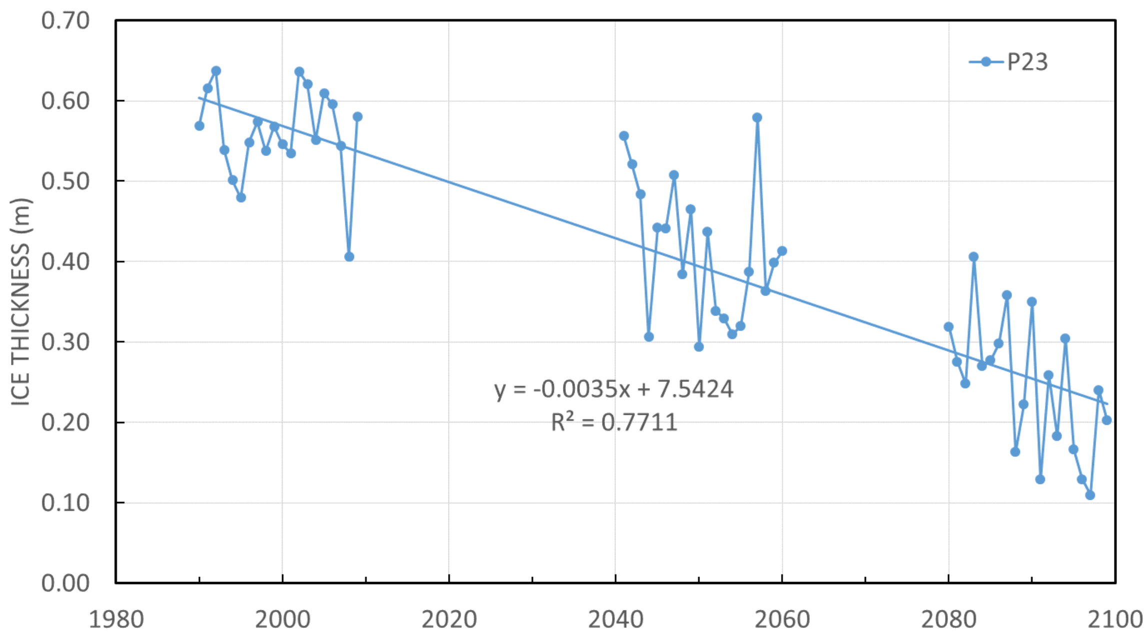

A7
ICE THICKNESS (m)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1980
2000
2020
2040
2060
2080
2100
y = -0.0032x + 6.8515
R² = 0.7877


D4
ICE THICKNESS (m)
y = -0.0031x + 6.5814
R² = 0.7775
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1980
2000
2020
2040
2060
2080
2100

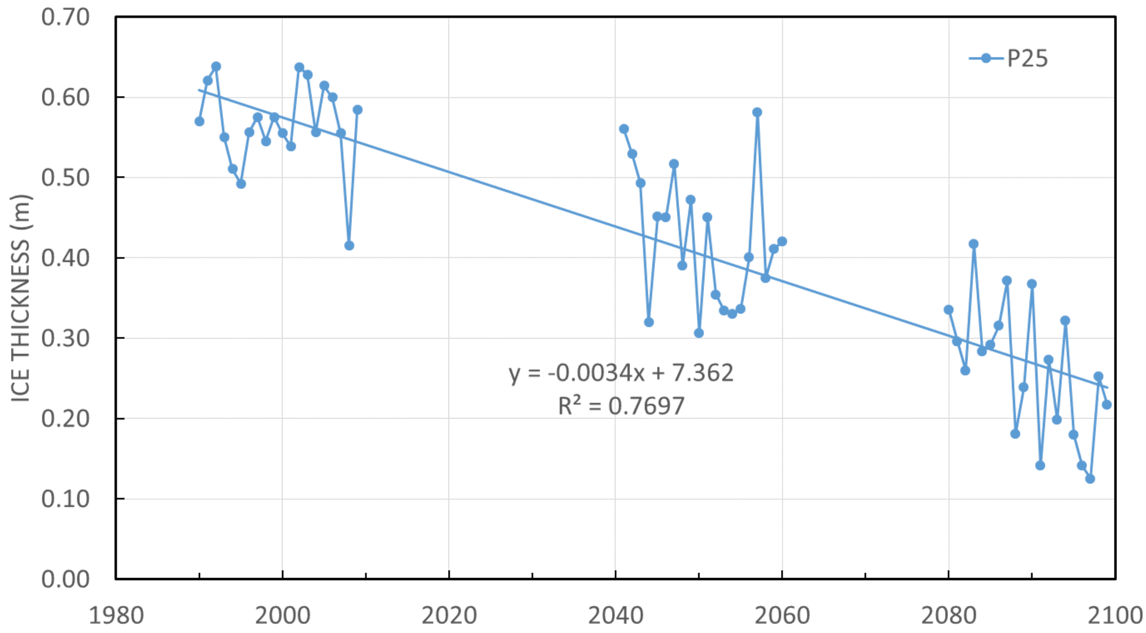

P6
ICE THICKNESS (m)
y = -0.0034x + 7.2399
R² = 0.7862
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1980
2000
2020
2040
2060
2080
2100

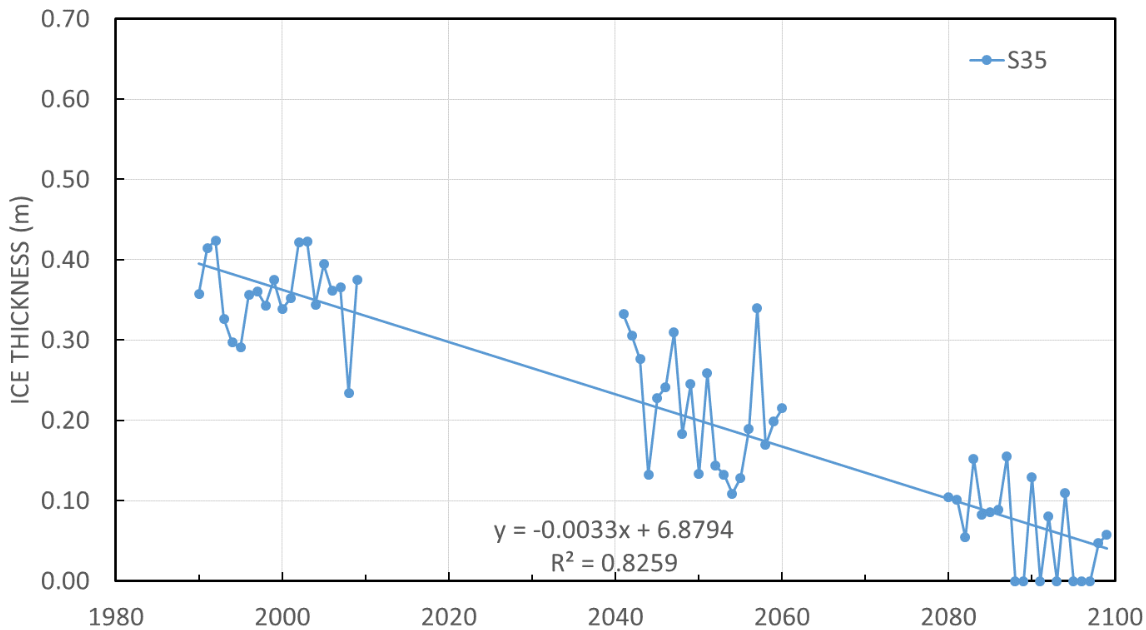


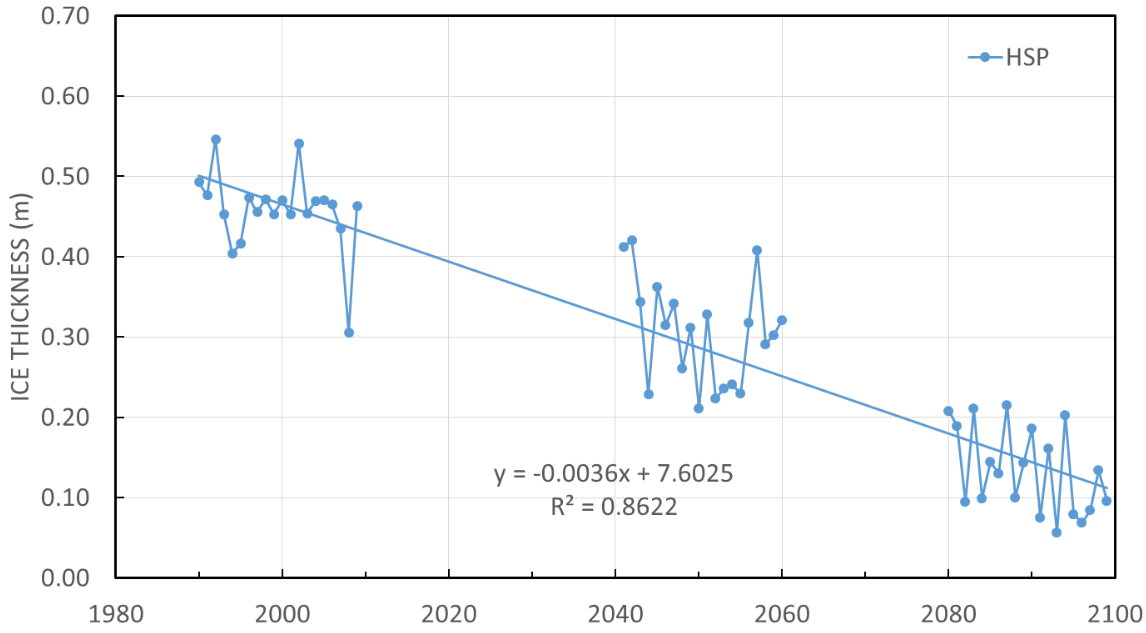
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ICE THICKNESS (m)
P11
y = -0.0033x + 7.0887
R² = 0.7416
1980
2000
2020
2040
2060
2080
2100



0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ICE THICKNESS (m)
P23
y = -0.0035x + 7.5424
R² = 0.7711
1980
2000
2020
2040
2060
2080
2100


0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ICE THICKNESS (m)
1980
2000
2020
2040
2060
2080
2100
P25
y = -0.0034x + 7.362
R² = 0.7697


0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ICE THICKNESS (m)
1980
2000
2020
2040
2060
2080
2100
S35
y = -0.0033x + 6.8794
R² = 0.8259



0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ICE THICKNESS (m)
1980
2000
2020
2040
2060
2080
2100
HSP
y = -0.0036x + 7.6025
R² = 0.8622

Appendix B: Preliminary tables of maximum annual ice thickness using CFDD method for the time periods 1990-2009, 2041-2060, and 2080-2099.

Period 1: 1990-2009

Year	A1 FDD(m)	A2 FDD(m)	A3 FDD(m)	A7 FDD(m)	D4 FDD(m)	P6 FDD(m)	P11 FDD(m)	P23 FDD(m)	P25 FDD(m)	S35 FDD(m)	HSP FDD(m)
1990	0.51	0.48	0.48	0.46	0.43	0.46	0.46	0.57	0.57	0.36	0.49
1991	0.50	0.48	0.48	0.46	0.44	0.49	0.49	0.62	0.62	0.41	0.48
1992	0.54	0.52	0.52	0.50	0.46	0.51	0.50	0.64	0.64	0.42	0.55
1993	0.48	0.45	0.45	0.43	0.39	0.44	0.44	0.54	0.55	0.33	0.45
1994	0.40	0.38	0.38	0.37	0.34	0.38	0.38	0.50	0.51	0.30	0.40
1995	0.37	0.34	0.34	0.33	0.29	0.35	0.34	0.48	0.49	0.29	0.42
1996	0.44	0.41	0.41	0.40	0.36	0.40	0.41	0.55	0.56	0.36	0.47
1997	0.49	0.47	0.47	0.45	0.43	0.45	0.44	0.57	0.58	0.36	0.46
1998	0.41	0.39	0.39	0.38	0.35	0.40	0.40	0.54	0.55	0.34	0.47
1999	0.48	0.45	0.45	0.43	0.41	0.45	0.45	0.57	0.58	0.37	0.45
2000	0.45	0.42	0.42	0.40	0.36	0.41	0.41	0.55	0.56	0.34	0.47
2001	0.45	0.43	0.43	0.41	0.39	0.42	0.42	0.53	0.54	0.35	0.45
2002	0.53	0.51	0.51	0.49	0.46	0.51	0.51	0.64	0.64	0.42	0.54
2003	0.52	0.50	0.50	0.48	0.47	0.49	0.48	0.62	0.63	0.42	0.45
2004	0.43	0.41	0.41	0.39	0.37	0.40	0.40	0.55	0.56	0.34	0.47
2005	0.50	0.48	0.48	0.47	0.44	0.49	0.49	0.61	0.61	0.39	0.47
2006	0.47	0.45	0.45	0.43	0.41	0.45	0.44	0.60	0.60	0.36	0.46
2007	0.46	0.43	0.43	0.42	0.38	0.42	0.42	0.54	0.56	0.37	0.43
2008	0.33	0.30	0.30	0.29	0.27	0.29	0.29	0.41	0.42	0.23	0.31
2009	0.47	0.45	0.45	0.43	0.40	0.44	0.44	0.58	0.58	0.37	0.46
average	0.46	0.44	0.44	0.42	0.39	0.43	0.43	0.56	0.57	0.36	0.46
Stdev	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05
COV	0.12	0.12	0.12	0.13	0.14	0.13	0.12	0.10	0.09	0.13	0.11

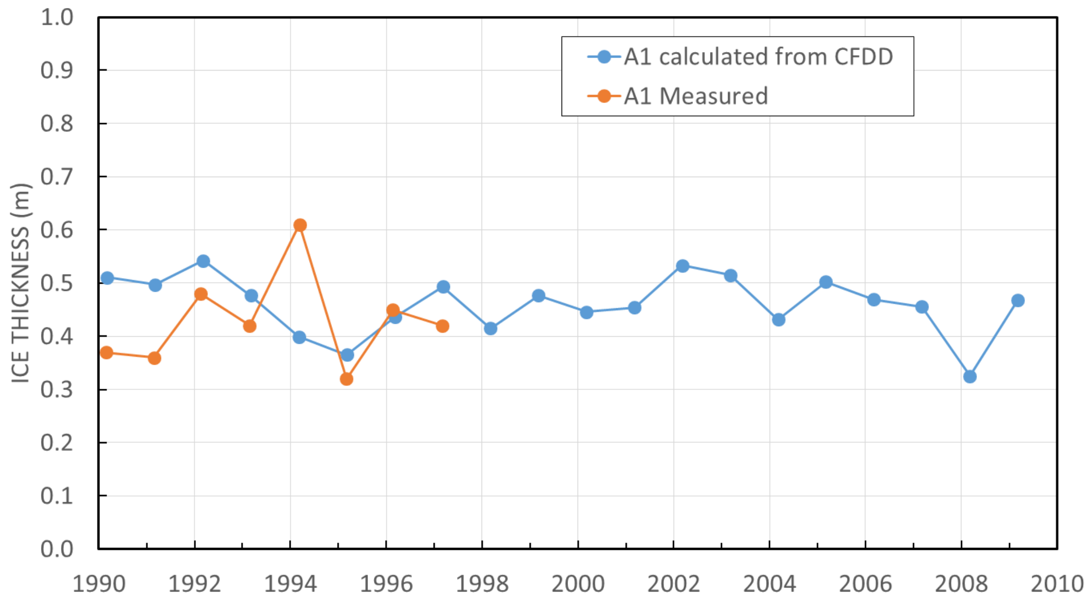
Period 2: 2041-2060

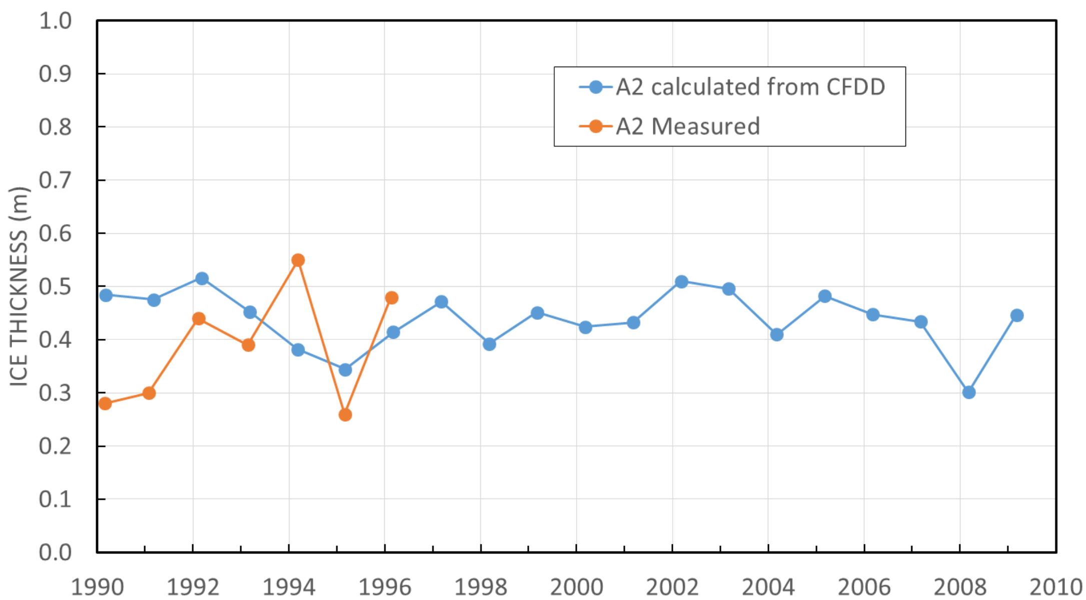
Year	A1 FDD(m)	A2 FDD(m)	A3 FDD(m)	A7 FDD(m)	D4 FDD(m)	P6 FDD(m)	P11 FDD(m)	P23 FDD(m)	P25 FDD(m)	S35 FDD(m)	HSP FDD(m)
2041	0.44	0.41	0.41	0.40	0.37	0.42	0.45	0.56	0.56	0.33	0.41
2042	0.44	0.42	0.42	0.40	0.37	0.40	0.46	0.52	0.53	0.31	0.42
2043	0.38	0.36	0.36	0.34	0.32	0.36	0.39	0.48	0.49	0.28	0.34
2044	0.21	0.19	0.19	0.18	0.15	0.18	0.23	0.31	0.32	0.13	0.23
2045	0.33	0.30	0.30	0.28	0.25	0.29	0.34	0.44	0.45	0.23	0.36
2046	0.35	0.33	0.33	0.32	0.30	0.32	0.37	0.44	0.45	0.24	0.32
2047	0.45	0.43	0.43	0.41	0.39	0.42	0.47	0.51	0.52	0.31	0.34
2048	0.32	0.30	0.30	0.28	0.26	0.28	0.33	0.38	0.39	0.18	0.26
2049	0.36	0.34	0.34	0.33	0.30	0.33	0.38	0.46	0.47	0.25	0.31
2050	0.21	0.19	0.19	0.18	0.17	0.18	0.23	0.29	0.31	0.13	0.21
2051	0.35	0.33	0.33	0.32	0.29	0.34	0.36	0.44	0.45	0.26	0.33
2052	0.26	0.24	0.24	0.23	0.20	0.23	0.28	0.34	0.35	0.14	0.22
2053	0.25	0.23	0.23	0.21	0.18	0.19	0.27	0.33	0.33	0.13	0.24
2054	0.24	0.21	0.21	0.19	0.17	0.18	0.25	0.31	0.33	0.11	0.24
2055	0.23	0.21	0.21	0.19	0.17	0.17	0.25	0.32	0.34	0.13	0.23
2056	0.29	0.27	0.27	0.25	0.22	0.26	0.31	0.39	0.40	0.19	0.32
2057	0.48	0.45	0.45	0.43	0.41	0.44	0.5	0.58	0.58	0.34	0.41
2058	0.27	0.25	0.25	0.23	0.21	0.23	0.28	0.36	0.38	0.17	0.29
2059	0.31	0.29	0.29	0.28	0.26	0.28	0.33	0.40	0.41	0.20	0.30
2060	0.28	0.26	0.26	0.24	0.22	0.25	0.29	0.41	0.42	0.21	0.32
average	0.32	0.30	0.30	0.28	0.26	0.29	0.34	0.41	0.42	0.21	0.31
Stdev	0.08	0.08	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.07	0.07
COV	0.26	0.28	0.28	0.29	0.31	0.31	0.24	0.21	0.20	0.34	0.21

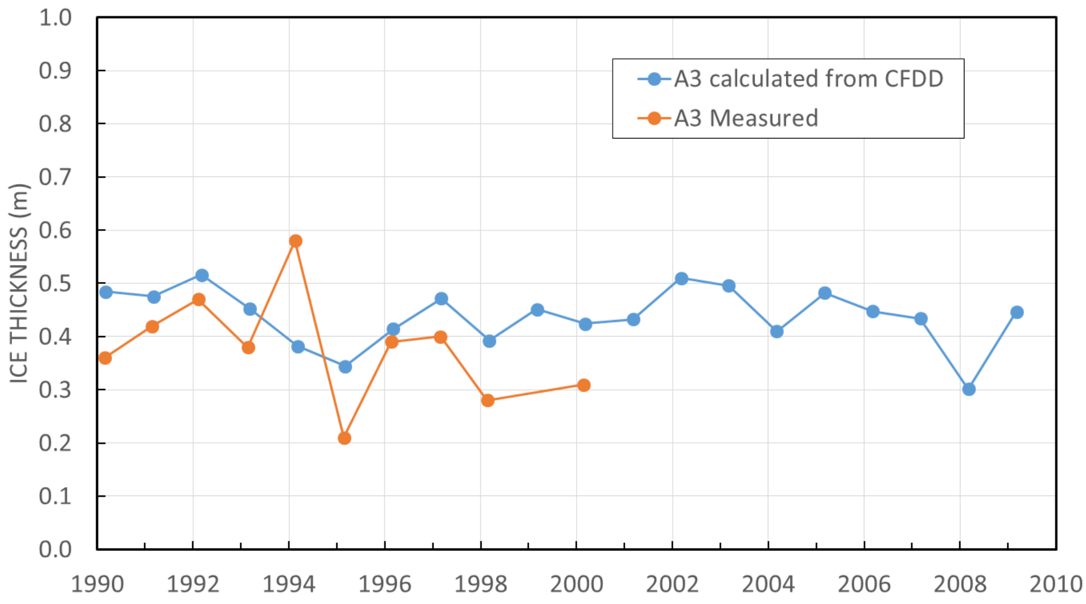
Period 3: 2080-2199

Year	A1 FDD(m)	A2 FDD(m)	A3 FDD(m)	A7 FDD(m)	D4 FDD(m)	P6 FDD(m)	P11 FDD(m)	P23 FDD(m)	P25 FDD(m)	S35 FDD(m)	HSP FDD(m)
2080	0.26	0.24	0.24	0.22	0.19	0.21	0.20	0.32	0.34	0.10	0.21
2081	0.17	0.14	0.14	0.13	0.11	0.13	0.13	0.28	0.30	0.10	0.19
2082	0.19	0.18	0.18	0.16	0.15	0.15	0.14	0.25	0.26	0.05	0.09
2083	0.28	0.25	0.25	0.24	0.20	0.24	0.24	0.41	0.42	0.15	0.21
2084	0.21	0.19	0.19	0.18	0.16	0.16	0.16	0.27	0.28	0.08	0.10
2085	0.18	0.18	0.18	0.16	0.13	0.15	0.15	0.28	0.29	0.09	0.14
2086	0.22	0.19	0.19	0.18	0.16	0.18	0.18	0.30	0.32	0.09	0.13
2087	0.25	0.23	0.23	0.21	0.20	0.23	0.23	0.36	0.37	0.16	0.22
2088	0.09	0.07	0.07	0.06	0.03	0.05	0.05	0.16	0.18	0.00	0.10
2089	0.12	0.10	0.10	0.09	0.06	0.08	0.08	0.22	0.24	0.00	0.14
2090	0.26	0.24	0.24	0.22	0.20	0.22	0.22	0.35	0.37	0.13	0.19
2091	0.07	0.06	0.06	0.05	0.05	0.03	0.03	0.13	0.14	0.00	0.08
2092	0.18	0.16	0.16	0.15	0.13	0.14	0.13	0.26	0.27	0.08	0.16
2093	0.12	0.10	0.10	0.09	0.07	0.08	0.08	0.18	0.20	0.00	0.06
2094	0.20	0.18	0.18	0.17	0.15	0.17	0.16	0.30	0.32	0.11	0.20
2095	0.11	0.09	0.09	0.08	0.05	0.06	0.06	0.17	0.18	0.00	0.08
2096	0.08	0.06	0.06	0.05	0.03	0.05	0.06	0.13	0.14	0.00	0.07
2097	0.04	0.03	0.03	0.02	0.01	0.01	0.00	0.11	0.13	0.00	0.08
2098	0.15	0.13	0.13	0.11	0.10	0.12	0.12	0.24	0.25	0.05	0.13
2099	0.13	0.11	0.11	0.10	0.08	0.09	0.09	0.20	0.22	0.06	0.10
average	0.17	0.15	0.15	0.13	0.11	0.13	0.13	0.25	0.26	0.06	0.13
Stdev	0.07	0.07	0.07	0.06	0.06	0.07	0.07	0.08	0.08	0.05	0.05
COV	0.42	0.46	0.46	0.49	0.55	0.54	0.53	0.34	0.32	0.87	0.40

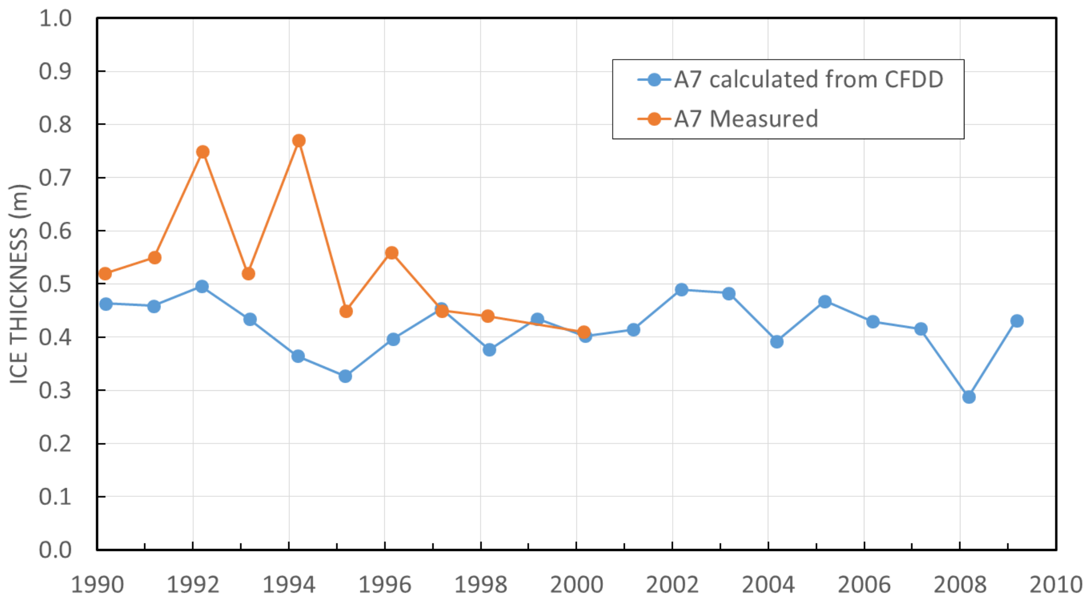
Appendix C: Preliminary plots of maximum annual ice thickness from 1990-2009, comparing CFDD method with ECCC on-ice measurements


A1 calculated from CFDD
A1 Measured
ICE THICKNESS (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

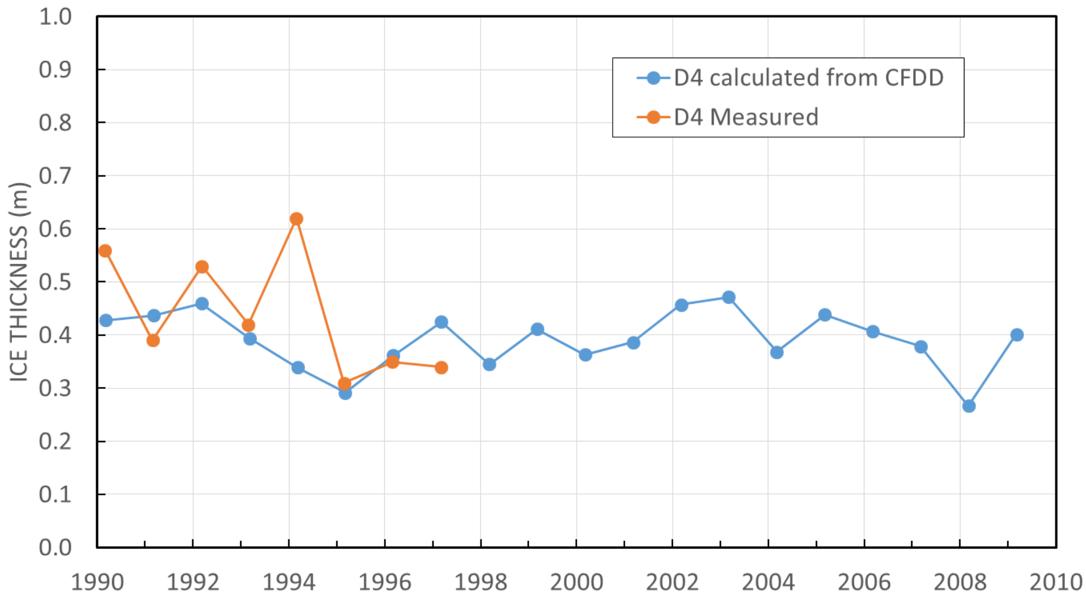

A2 calculated from CFDD
A2 Measured
ICE THICKNESS (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010



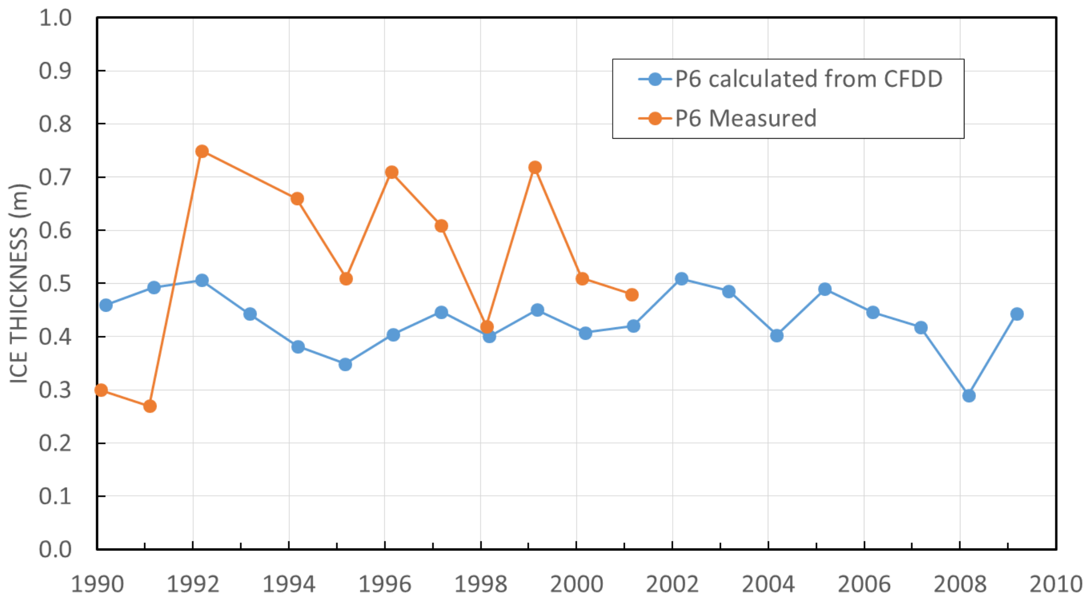
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
A3 calculated from CFDD
A3 Measured
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010



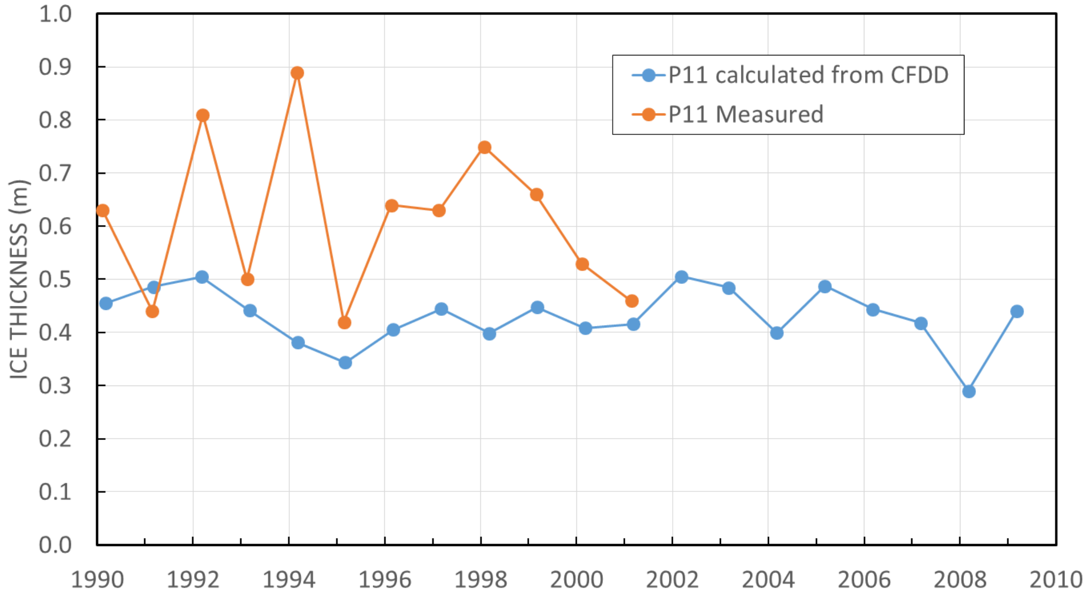
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
A7 calculated from CFDD
A7 Measured
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

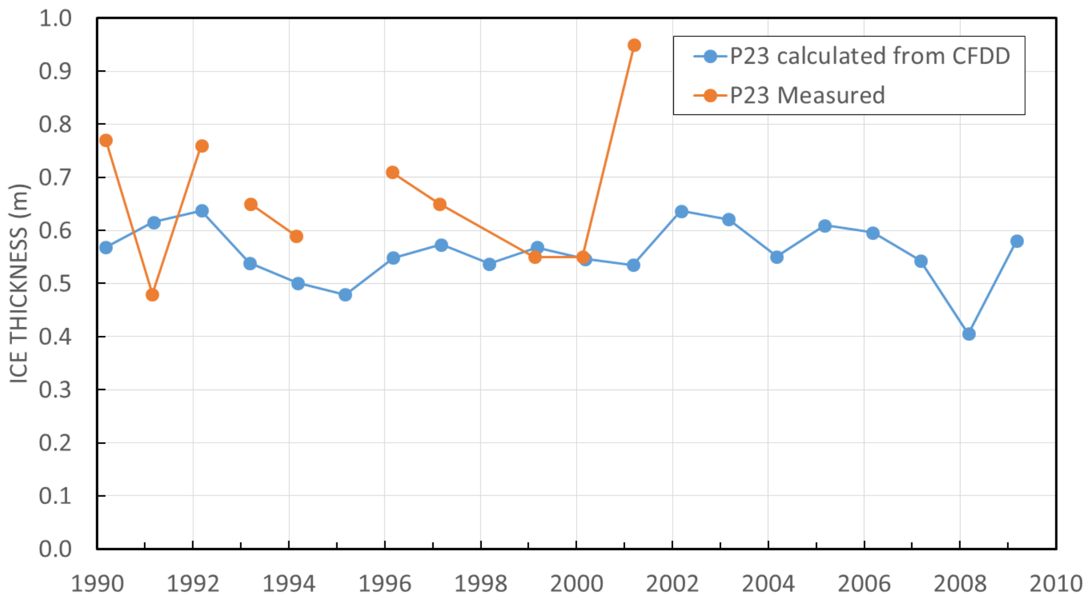


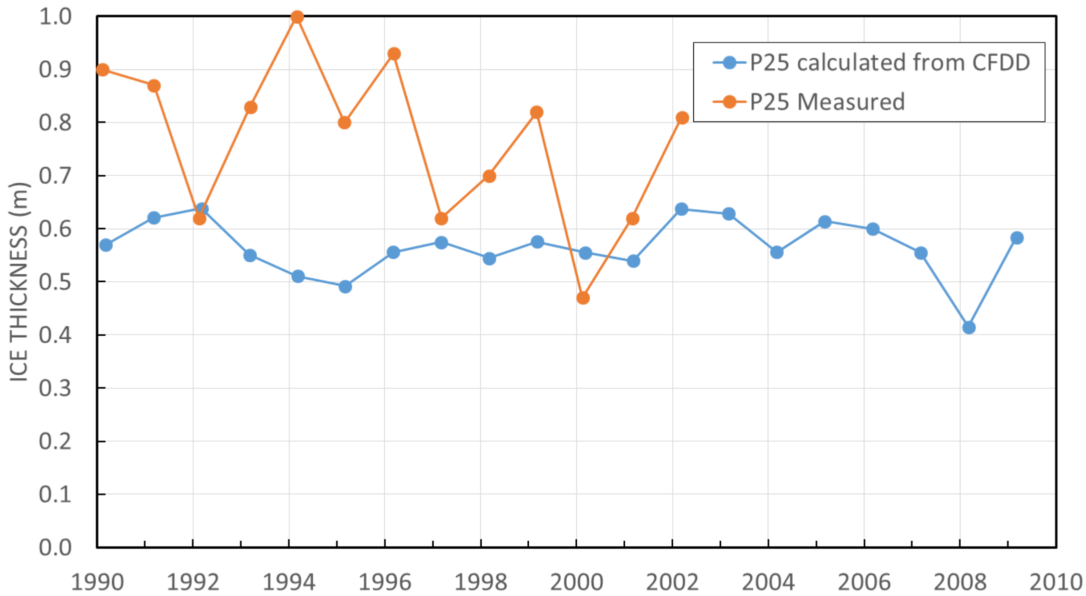
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
D4 calculated from CFDD
D4 Measured
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

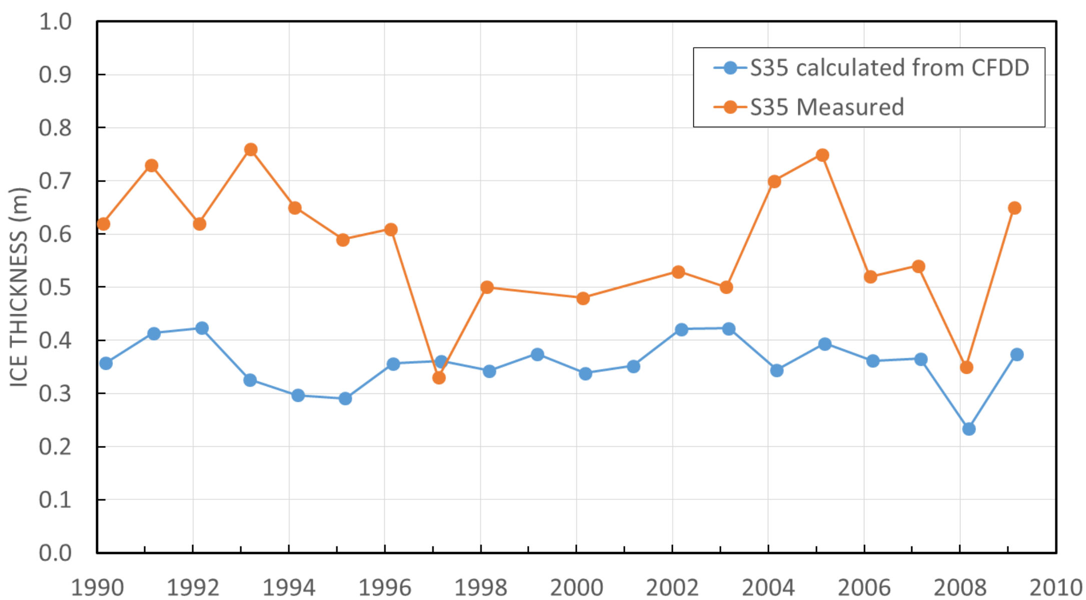


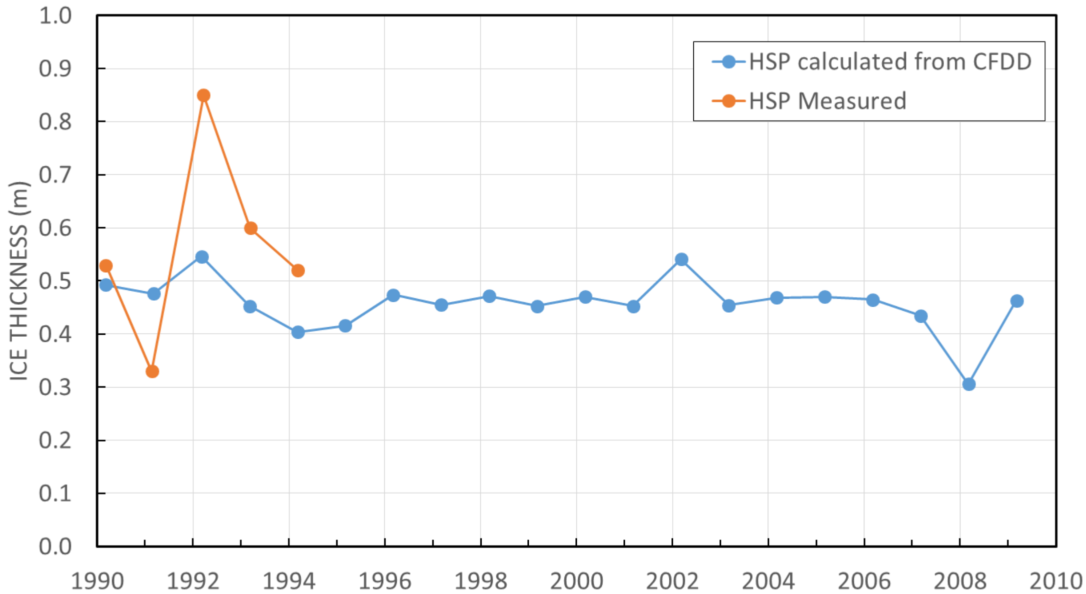
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
P6 calculated from CFDD
P6 Measured
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
P11 calculated from CFDD
P11 Measured


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
P23 calculated from CFDD
P23 Measured


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
P25 calculated from CFDD
P25 Measured


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
S35 calculated from CFDD
S35 Measured


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ICE THICKNESS (m)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
HSP calculated from CFDD
HSP Measured