

Validation of the North American Ice Service Iceberg Drift Model

Adam Garbo

A thesis submitted in partial fulfillment of the requirements for the
Master of Science degree in Physical Geography

Department of Geography, Environment and Geomatics
Faculty of Arts
University of Ottawa

Supervisors

Dr. Luke Copland

Dr. Derek Mueller

Thesis Committee

Dr. Adrienne Tivy

Dr. Anders Knudby

Abstract

Icebergs calved from high-latitude glaciers and ice shelves pose a threat to vessels and offshore infrastructure at a time when Arctic shipping and resource exploration are increasing. Knowledge of the location of potential ice hazards is therefore critical to ensure safe and efficient operations in this remote region. The Canadian Ice Service (CIS; Environment and Climate Change Canada) provides information to stakeholders on the observed and predicted distribution of icebergs in Canadian waters by combining iceberg observations with forecasts from the North American Ice Service (NAIS) iceberg drift model. The NAIS model estimates the forces acting on an iceberg to predict its future position and velocity. It is widely used for the east coast of Canada but largely unproven in the Arctic and suffers from insufficient validation due to a paucity of reliable *in-situ* observations of iceberg drift.

This study represents the first comprehensive validation of the NAIS iceberg drift model for the Canadian Arctic. A total of 133 hindcast simulations for the period 2009-2019 were performed against *in-situ* drift observations of 44 icebergs. These data, collated in an iceberg beacon database (compiled by Carleton University and CIS), includes observations collected by Cryologgers; novel iceberg tracking beacons designed as part of this study. Quantified comparisons of the distance error between observed and modelled drift tracks indicate that the NAIS model produces realistic simulations of iceberg drift in Baffin Bay. Root mean square error after 24-hours of simulated drift ranged from 18-22 km and increased at a daily rate of 11-13 km, which is typical of previous model verification and validation studies. Improved model performance was observed for longer (>250 m) and deeper-keeled (>100 m) icebergs, which appears to counteract the model's tendency to overestimate drift by reducing the influence of stronger surface ocean currents acting on the iceberg. Ocean current direction, wind direction, and iceberg keel geometry were identified by a sensitivity analysis as the model parameters and environmental driving forces that have the greatest influence on modelled iceberg drift. These results emphasize the need for accurate environmental information and underscore the importance of properly representing the physical characteristics of icebergs in drift models.

Acknowledgements

First, I would like to express my sincere appreciation to my supervisors: Dr. Luke Copland (University of Ottawa) and Dr. Derek Mueller (Carleton University) for their continued support and guidance throughout this project. Together, you have provided numerous opportunities for field research, collaborative projects, and conference participation, of which I am extremely grateful. Luke, your knowledge, mentorship and insightful feedback have helped me to grow as a scientist. Derek, thank you for introducing me to the world of cryospheric research those many years ago, sharing your passion for innovation, and fostering my passion for technology.

I would like to acknowledge my thesis committee: Dr. Adrienne Tivy and Dr. Anders Knudby for their helpful comments and suggestions. Many thanks to Philippe Lamontagne of the National Research Council of Canada for providing the iceberg drift model upon which this thesis was based, and Hai Tran of the Canadian Ice Service and Dr. Gregory Smith of Environment and Climate Change Canada for their help in acquiring the data needed to run the model. Thanks also to Dr. Juliana Marson from the University of Manitoba for her invaluable data processing assistance. My field research would not have been possible without the support provided by ArcticNet Network of Centres of Excellence Canada, Amundsen Science, and the crew of the CCGS Amundsen. I would like to extend a special thanks to helicopter pilots Dick Morissette and Sébastien Tremblay. The opportunity to land and work on icebergs in the Canadian Arctic was a truly unforgettable experience.

Finally, I would like to thank my friends and family for their unwavering support throughout this endeavor. I am especially grateful to Anna Crawford, who was always willing and enthusiastic to assist in any way she could. To my partner Annika, who now knows more about iceberg drift modelling than you she ever expected, thank you for lending me a listening ear and for the comforting words you always seem to find. You are a constant source of encouragement.

Support for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) Canadian Graduate Scholarship, Northern Scientific Training Program (NSTP), ArcticNet Network of Centres of Excellence Canada, Canada Foundation for Innovation, Ontario Research Fund, Luke Copland's NSERC Discovery Grant and Northern Supplement and the Department of Geography, Environment and Geomatics, University of Ottawa.

Table of Contents

Abstract	ii
Acknowledgements	iii
List of Tables	vii
List of Figures	ix
List of Abbreviations	xiv
Chapter 1: Introduction	1
1.1 Research Objectives	2
1.2 Thesis Structure	3
1.3 Study area	3
1.3.1 Baffin Bay	3
1.3.2 Labrador Sea	4
Chapter 2: Background	6
2.1 Iceberg morphology	6
2.2 Iceberg production	7
2.2.1 Greenland	8
2.2.2 Canadian Arctic	10
2.3 Iceberg drift	11
2.3.1 Factors influencing drift	11
2.3.2 Iceberg drift tracking	13
2.4 Iceberg deterioration	14
2.4.1 Surface melting due to solar radiation	14
2.4.2 Melting due to buoyant vertical convection	15
2.4.3 Melting due to forced convection	15
2.4.4 Wave erosion	16
2.4.5 Calving	17
2.5 Iceberg drift and deterioration modelling	17
2.5.1 Modelling iceberg drift	17
2.5.2 Modelling iceberg deterioration	19
2.5.3 Model temporal and spatial scales	20
2.5.4 Determining drift model skill	21
2.5.5 Sensitivity analysis	22
2.5.6 Operational iceberg drift and deterioration modelling	23
Chapter 3: Datasets and Methodology	25

3.1	Iceberg drift tracking beacons.....	25
3.1.1	Hardware.....	25
3.1.2	Software	26
3.1.3	Deployments	27
3.2	Iceberg tracking beacon database	29
3.2.1	Data selection.....	30
3.2.2	Data processing.....	32
3.2.3	Iceberg dimensions	33
3.2.4	Data standardization.....	34
3.3	Environmental input data.....	36
3.3.1	Wind and wave conditions.....	36
3.3.2	Ocean currents	37
3.4	North American Ice Service iceberg drift model.....	40
3.4.1	Model operation.....	40
3.4.2	Sail and keel calculations.....	42
3.5	Model validation	44
3.5.1	Error statistics	45
3.5.2	Comparison of ocean current sources	46
3.5.3	Spatio-temporal variability of model performance.....	46
3.5.4	Factors affecting model performance	47
3.6	Sensitivity analysis.....	47
Chapter 4:	Results.....	49
4.1	Iceberg drift tracking beacons.....	49
4.1.1	Operation.....	49
4.1.2	Iceberg drift.....	50
4.2	Model validation	52
4.2.1	Comparison of ocean current models	53
4.2.2	Temporal variability of model performance	63
4.2.3	Factors influencing model performance	65
4.2.4	Spatio-temporal variability of model performance.....	67
4.3	Sensitivity analysis.....	70
4.3.1	Iceberg waterline length.....	74
4.3.2	Keel depth	75
4.3.3	Air drag coefficient.....	76

4.3.4	Water drag coefficient.....	77
4.3.5	Wind speed & direction	78
4.3.6	Ocean current direction & speed.....	80
4.3.7	Significant height & direction of wind waves	81
4.3.8	Significant height & direction of swell waves.....	83
Chapter 5:	Discussion	85
5.1	Iceberg drift tracking beacons.....	85
5.1.1	Operation.....	85
5.1.2	Estimates of iceberg morphology	87
5.1.3	Iceberg drift.....	87
5.2	Model validation	89
5.2.1	Bias of iceberg drift observations	89
5.2.2	Model performance	90
5.2.3	Comparison of modelled ocean currents.....	95
5.3	Sensitivity analysis.....	99
5.3.1	Iceberg waterline length.....	99
5.3.2	Keel depth	100
5.3.3	Air drag coefficient	102
5.3.4	Water drag coefficient.....	103
5.3.5	Wind speed & direction	104
5.3.6	Ocean current speed & direction.....	105
5.3.7	Wind wave height & direction.....	106
5.3.8	Swell wave height & direction.....	107
Chapter 6:	Conclusion	108
References		112
Appendix A:		123
Appendix B:		124

List of Tables

Table 2.1: Iceberg size classifications from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (Canadian Ice Service, 2005).	7
Table 2.2: Average iceberg height to draft ratios from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (Canadian Ice Service, 2005).	7
Table 2.3: Average contributions of iceberg deterioration mechanisms to mass loss. Based on studies of icebergs off the coast of Newfoundland and Labrador (El-Tahan et al., 1987).	20
Table 3.1: Electronic components and associated costs for Cryologger iceberg tracking beacons (v1.0/2.0) in 2021.	26
Table 3.2: Remote-sensing imagery and resolutions used to determine iceberg size and shape classification information.	34
Table 3.3: Wind and wave environmental input data variables acquired from the ERA5 reanalysis at 1-hour resolution for the period January 1, 2009, to December 31, 2019.	37
Table 3.4: Initial iceberg conditions required to run the NAIS iceberg drift model.	40
Table 3.5: List of environmental variables required to run the NAIS iceberg drift model and data sources selected for use in this study.	41
Table 3.6: List of coefficients used by the NAIS iceberg drift model and default values used in this study.	42
Table 3.7: Estimated dimensions, MANICE iceberg shape classifications, durations and locations of icebergs used in the sensitivity analysis.	48
Table 4.1: Operational lifespan, maximum speed and cumulative distance travelled for Cryologger iceberg tracking beacons deployed in 2018 and 2019, as of December 1, 2021.	50
Table 4.2: Mean absolute error and coefficient of variation of hindcast simulations of iceberg drifting using CECOM and GLORYS modelled ocean currents for the period 2009-2019. Mean values calculated from all timesteps of hindcast simulations.	55
Table 4.3: RMSE and scaled RMSE distance of hindcast simulations of iceberg drifting using CECOM and GLORYS ocean current models for the period 2009-2019. Count denotes number of iceberg tracks used in statistical calculations at each duration. Mean values calculated from all timesteps of hindcast simulations.	57

Table 4.4: Mean absolute error and coefficient of variation of hindcast simulations of iceberg drifting using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. Mean values calculated from all timesteps of hindcast simulations.	60
Table 4.5: RMSE and scaled RMSE of hindcast simulations of iceberg drifting using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. Count denotes number of iceberg tracks used in statistical calculations at each duration. Mean values calculated from all timesteps of hindcast simulations.	63
Table 4.6: Number of iceberg tracks included in each season for the 2009-2019 and 2017-2019 hindcast periods.	64
Table 4.7 Model input parameters and environmental driving forces examined in the sensitivity analysis, including the range of values and perturbation intervals used.	72

List of Figures

Figure 1.1: Study area of interest and main currents influencing iceberg drift from West Greenland glaciers to the Grand Banks of Newfoundland (area delineated by the dashed line) (ECCC, 2019a).	5
Figure 2.1: Bar plots of: (a) annual count and (b) monthly averages of icebergs crossing south of 48°N latitude between 1900-2020 (IIP, 2020).	8
Figure 2.2: Map of major sources of Greenland iceberg production and drift paths of icebergs (Diemand, 2001).	9
Figure 2.3: Locations and rates of iceberg production in the Queen Elizabeth Islands (QEI) for 2012 (Mueller et al., 2013).	11
Figure 2.4: Mechanisms of iceberg deterioration: (left) melting due to solar radiation and (right) buoyant vertical convection (ECCC, 2019a).	15
Figure 2.5: Mechanisms of iceberg deterioration: (left) Forced convection of wind and water currents and (right) wave erosion creating a wave notch and subsequent calving of an overhanging slab (ECCC, 2019a).	16
Figure 2.6: Example of a daily iceberg analysis chart produced by the North American Ice Service (NAIS) iceberg drift model (ECCC, 2019b).	24
Figure 3.1: Example of an assembled Cryologger v1.0 drift tracking beacon prior to deployment in 2018 (left) and a diagram of the assembled beacon electronics (right).	27
Figure 3.2: Locations of Cryologger iceberg drift tracking beacons deployed during the 2018, 2019 and 2021 field seasons.	28
Figure 3.3: Examples of icebergs instrumented with Cryologger tracking beacons and estimated length and freeboard measurements. Deployments made on September 3, 2018, along the southern coast of Baffin Island, NU (top/left) and July 30, 2019, near Devon Island, NU (bottom right). ..	29
Figure 3.4: Spatial distribution of the 44 iceberg tracks extracted from the iceberg beacon database that were cleaned and trimmed to a maximum duration of 28 days. Study area outlined in red. ..	31
Figure 3.5: Histograms of: (a) duration of suitable iceberg tracks extracted from the iceberg beacon database, and (b) the temporal distribution of observations contained in all tracks. No tracks contained observations during the period of December to February.	31

Figure 3.6: Examples of 7-day rolling: (a) mean and (b) standard deviation of iceberg beacon sea-surface temperatures (SST) used to determine the date and time at which the beacon became dislodged from the iceberg.....	33
Figure 3.7: Total number of observations for each iceberg drift track and the number of interpolations required to standardize the data to a 1-hour interval.....	35
Figure 3.8: Example of an iceberg trajectory (IMEI: 300234062792490) with observations at 5-minute intervals and the resulting interpolated observations at the standardized 1-hour interval.	36
Figure 3.9: Domains of the ocean current models used in this study: (a) CECOM and (b) custom RIOPS subset.	39
Figure 3.10: Approximations of iceberg keel based on waterline length according to NAIS method data fitting curve (red line), and idealized empirical relationship established by Barker et al. (2004) (blue line).	43
Figure 3.11: Relationships between iceberg waterline length and keel depth based on above- and below-water field surveys of icebergs in the Arctic (Schild et al., 2021).....	44
Figure 3.12: Relationships between iceberg waterline length and keel depths based of the 44 icebergs selected from the iceberg beacon database for use in this study. Regression line shown as thick black line.	44
Figure 4.1: Iceberg drift tracks recorded by Cryologger beacon deployments made during the 2018 field season.....	51
Figure 4.2: Iceberg drift tracks recorded by Cryologger beacon deployments made during the 2019 field season.....	52
Figure 4.3: Examples of observed and modelled iceberg tracks illustrating the variability in performance of hindcast simulations of iceberg drift. Both tracks are 96 hours in duration. Markers are placed at 3-hour intervals.	53
Figure 4.4: Distance error between modelled and observed positions for all 133 hindcast simulations of iceberg drift using: (a) CECOM, and (b) GLORYS modelled ocean currents for the period 2009-2019. Thin gray lines represent each hindcast simulation and the thick coloured line is the mean error distance for all model runs.	54
Figure 4.5: Histograms of 96-hour: (a, b) final distance error, and (c, d) cumulative distance error for 112 hindcast simulations of iceberg drift (positive values indicate overestimation of iceberg	

drift distance by the model, and vice versa for negative values) using CECOM and GLORYS modelled ocean currents for the period 2009-2019. Mean values denoted by dashed lines.....	56
Figure 4.6: RMSE distance of hindcast simulations of iceberg drift throughout: (a) 24 hours, and (b) 96 hours, using CECOM and GLORYS modelled ocean currents for the period 2009-2019. For the 96-hour plot, there are 133, 121, 112, and 97 drift tracks that extend up to 24, 48, 72, and 96-hour hindcast durations, respectively. Dotted area in panel (a) represents zoomed area of panel (b).	58
Figure 4.7: Distance error between modelled and observed positions for all 63 hindcast simulations of iceberg drift using: (a) CECOM, (b) GLORYS, and (c) RIOPS modelled ocean currents for the period 2017-2019. Thin gray lines represent each hindcast simulation and thick lines are the overall mean distance error for all model runs.	59
Figure 4.8: Histograms of 96-hour: (a, b, c) final distance error and (d, e, f) cumulative distance error for hindcast simulations of iceberg drift (positive values indicate overestimation of iceberg drift distance by the model, and vice versa for negative values) using CECOM, GLORYS, and RIOPS modelled ocean currents for the period 2017-2019. Mean values denoted by dashed line.	61
Figure 4.9: RMSE distance of hindcast simulations of iceberg drift at: (a) 96 hours, and (b) 24 hours using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. In plot (b) there are 63, 55, 47, and 42 drift tracks that extend up to 24, 48, 72, and 96-hour hindcast durations, respectively. Dotted area in panel (a) represents 24-hour zoomed area in panel (b)... ..	62
Figure 4.10: Boxplots of: (a, c) final distance error, and (b, d) cumulative distance error as a function of season for all hindcast simulations of iceberg drift using: (a, b) CECOM and GLORYS modelled ocean currents for: (a, b) 2009-2019, and (c, d) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Boxplots illustrate inter-quartile range of 25 th to 75 th percentiles. Outliers denoted by diamonds.	65
Figure 4.11: Cumulative distance of observed iceberg tracks at 96-hours as a function of iceberg waterline length. Regression line and shaded 95% confidence interval are shown.....	66
Figure 4.12: RMSE as a function of iceberg waterline length for all hindcast simulations of iceberg drift using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.	67

Figure 4.13: RMSE as a function of the starting latitude of observed iceberg drift tracks for hindcast simulations using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.	68
Figure 4.14: RMS error distance for 24-hour hindcast simulations of iceberg drift: (a, b) north of 65°N; (c, d) south of 60°N using: (a, c) CECOM and (b, d) GLORYS modelled ocean currents for the period 2009-2019.	69
Figure 4.15: RMS error distance for 24-hour hindcast simulations of iceberg drift north of 65°N (top) and south of 60°N (bottom), using: (a, d) CECOM, (b, e) GLORYS, and (c, f) RIOPS modelled ocean currents for the period 2017-2019.	70
Figure 4.16: Pairwise comparisons of distance error between base case hindcast and perturbation levels ($n = 6$) calculated at each hourly time step for all hindcast simulations of iceberg drift used to assess the sensitivity of the NAIS model. Input parameters: a) iceberg length, b) iceberg keel depth, c) air drag coefficient, d) water drag coefficient, e) wind direction, f) wind speed, g) ocean current direction, h) ocean current speed, i) significant height of wind waves, j) direction of wind waves, k) significant height of swell waves, l) swell wave direction. Changes in wind and ocean current direction is to the left when positive and to the right when negative. Shading indicates 95% confidence interval.	73
Figure 4.17: Observed and modelled iceberg drift tracks illustrating the sensitivity of the NAIS model to changes in iceberg waterline length. Observed base values: (a) 250 m, (b) 245 m, (c) 420 m, (d) 145 m, (e) 134 m, (f) 127 m.	74
Figure 4.18: Observed and modelled iceberg drift tracks showing the sensitivity of the NAIS model to changes in iceberg keel depth. Observed base values: (a) 75 m, (b) 75 m, (c) 50 m, (d) 105 m, (e) 60 m, (f) 27 m.	76
Figure 4.19: Observed and modelled simulations of iceberg drift showing the sensitivity of the NAIS model to changes in air drag coefficient.	77
Figure 4.20: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in the water drag coefficient.	78
Figure 4.21: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in wind direction.	79

Figure 4.22: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in ocean current direction.	80
Figure 4.23: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in ocean current speed.	81
Figure 4.24: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in direction of wind waves.....	82
Figure 4.25: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in significant height of swell waves.	83
Figure 4.26: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in direction of swell waves.	84
Figure 5.1: Drift of iceberg instrumented with beacon 300434063415110 illustrating maximum drift speeds of 6 km h ⁻¹ and tidal current effects near Resolution Island, Nunavut between April 16-29, 2019.	88
Figure 5.2: RMSE as a function of iceberg keel depth for all hindcast simulations of iceberg drift using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; (b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.	94
Figure 5.3: Pairwise comparison of distance error for hindcast simulations of iceberg drift using various sources of modelled ocean currents: (a) CECOM vs. GLORYS (2009-2019), (b) CECOM vs. RIOPS (2017-2019), and (c) GLORYS vs. RIOPS (2017-2019). Each plot is annotated with the modelled ocean current that has improved distance error performance. Colours indicate individual hindcast simulations.....	Error! Bookmark not defined.
Figure 5.4: (a) Observed iceberg track recorded by beacon 300234060177480 over 96-hours between August 2-6, 2017, and modelled iceberg tracks using CECOM, GLORYS and RIOPS ocean currents. Markers placed every 3 hours. (b) Hourly surface (0-10 m) ocean current velocities acting on the iceberg for each modelled ocean current (Note: CECOM and GLORYS interpolated to hourly timesteps).....	98
Figure 5.5: (a) Distribution of cumulative distance travelled by icebergs (n=6) for each keel depth modifier. (b) Example of the variability of mean RIOPS ocean current speeds at different iceberg keel depth layers for iceberg C, located in Davis Strait.....	101

List of Abbreviations

BIC	Baffin Island Current
CAA	Canadian Arctic Archipelago
CECOM	Canadian East Coast Ocean Model
CMEMS	Copernicus Marine Environment Monitoring Service
CIS	Canadian Ice Service
IIP	International Ice Patrol
IICWG	International Ice Charting Working Group
GIS	Greenland Ice Sheet
GNSS	Global Navigation Satellite Systems
GLORYS	Global Ocean Reanalysis and Simulations
LAKI	Limit of All Known Ice
NAIS	North American Ice Service
NEMO	Nucleus for European Modeling of the Ocean
NRC	National Research Council of Canada
QEI	Queen Elizabeth Islands
RIOPS	Regional Ice Ocean Prediction System
RMS	Root mean square
RMSE	Root mean square error
WGC	West Greenland Current

Chapter 1: Introduction

Icebergs calved from high-latitude glaciers and ice shelves present a significant hazard to marine vessels and infrastructure at a time when demand for access to Arctic waters is increasing (Crocker et al., 2004; Fuglem & Jordaan, 2017). In the Canadian Arctic, ship traffic has increased more than 75% over the past decade (Dawson et al., 2018), and the continued reduction of Arctic sea ice is anticipated to further increase accessibility to marine activities, such as shipping, fishing, tourism, and natural resource extraction (Meier et al., 2014). Knowledge of the location and severity of these potential ice hazards, including icebergs, is critical for ensuring safe and efficient marine operations. However, observations from satellites, aerial reconnaissance and marine vessels are often obtained on an intermittent basis and over limited areas (Bigg et al., 2018; Savage, 2001a). Therefore, it is necessary to have numerical models that can forecast the drift and deterioration of icebergs to fill data gaps for periods between observations and predict the future locations and trajectories of these ice hazards.

The Canadian Ice Service (CIS) is responsible for providing daily charts and bulletins of observed and predicted distributions of icebergs to mariners navigating or operating offshore from Canada's east coast and in the Canadian Arctic. This is made possible by combining iceberg observations with forecasts from an iceberg drift and deterioration model. The current operational forecast model is referred to as the North American Ice Service (NAIS) iceberg drift model, which was developed at the National Research Council of Canada (NRC) and is currently implemented at the CIS (Kubat et al., 2005, 2007). The NAIS iceberg drift model considers the forces acting on an iceberg and uses environmental inputs such as winds, waves, and currents to predict its position and velocity at future time steps. The model has been used operationally offshore the east coast of Canada, including by end-users in the Grand Banks of Newfoundland, to predict iceberg movements in the vicinity of oil rigs (Kubat & Sayed, 2006). However, the model is largely untested in the Arctic, in part due to a paucity of reliable *in-situ* field observations of iceberg drift from this region (Carrieres et al., 2001; Eik, 2009).

Previous efforts to validate the model have relied on observations of iceberg drift collected primarily from the east coast of Canada (Carrieres et al., 2001; Kubat et al., 2005). To date, no large-scale validation studies of the NAIS iceberg drift model have been performed for the Canadian Arctic (A. Tivy, CIS, personal communication, February 10, 2019). There is a growing

demand for *in-situ* iceberg tracking data from the Arctic for use in model validation studies, yet the high cost of commercial tracking devices often prevents iceberg monitoring at the required spatial and temporal resolutions. With the recent compilation of a comprehensive database of *in-situ* iceberg tracking beacon drift trajectories in the Northern Hemisphere, this essential regional validation is now possible. This database has been compiled by Carleton University, in cooperation with the CIS and is referred to here as the “iceberg beacon database”. The database contains over 160 iceberg trajectories between 1997 and 2022 and includes basic iceberg information such as shape and size classification. Using this unprecedented dataset, together with new iceberg tracking beacon deployments specific to this project, it will be possible to perform the first-ever large-scale model validation of the NAIS iceberg model in the Canadian Arctic.

1.1 Research Objectives

The overall aim of the project is to assess the performance of NAIS model predictions of iceberg drift in Canadian Arctic and sub-Arctic waters. This will be accomplished by fulfilling the following objectives:

1. Continue development and deployment of novel iceberg drift tracking beacons to assess the viability of low-cost, open-source technologies for the collection of high spatial and temporal resolution iceberg drift data and incorporate these into the iceberg beacon database.
2. Perform validation of the NAIS iceberg drift model against observed iceberg trajectories catalogued in the iceberg beacon database and assess the suitability of the model for use in locations beyond its current operational use through quantified comparisons of model performance.
3. Investigate the potential for improvement to the NAIS iceberg drift model through comparisons of model performance using both current and next generation high-resolution ocean current models and reanalysis products.
4. Conduct a sensitivity analysis of the NAIS iceberg drift model to various input parameters and environmental forcing data to determine if additional tuning of the model is required for iceberg morphologies and environmental conditions characteristic of the Baffin Bay region.

To meet the above objectives, a wide range of model input data sources, consisting of *in-situ* iceberg measurements, modelled environmental driving forces and remote sensing data, will be used to perform a comprehensive assessment of the performance of the NAIS iceberg model. The results of this study will provide important knowledge regarding model performance and may also be used to refine the parameterizations affecting iceberg drift. This research will be complementary to work being undertaken by the International Ice Charting Working Group (IICWG) and the International Ice Patrol to improve iceberg model outputs in support of maritime safety. In addition, this research will contribute to ongoing efforts by the NRC to develop and enhance the ability of the NAIS iceberg drift model to forecast the trajectory of icebergs more accurately. This will improve the quality of iceberg forecasts for the Arctic, which will contribute to safe and efficient marine operations in this region.

1.2 Thesis Structure

This thesis follows the traditional format. This Introduction chapter is followed by a Background in Chapter 2 that provides a brief overview of the origin, drift, and deterioration of icebergs, as well as an overview of current knowledge of iceberg drift modelling. Datasets and Methods used to undertake this study are presented in Chapter 3. Results are described in Chapter 4, Chapter 5 presents a Discussion and Chapter 6 is the Conclusion. A complete reference list is provided at the end of the document. Figures and tables are embedded within the text throughout the thesis. Detailed information of Cryologger iceberg tracking beacon deployments is included in Appendix A. Hindcast iceberg drift model simulation outputs are provided in Appendix B.

1.3 Study area

This study examines the paths of drifting icebergs within Canadian waters and covers a wide area extending from northern Baffin Bay to the southern Labrador Sea (Figure 1.1).

1.3.1 Baffin Bay

Baffin Bay connects to the Arctic Ocean through Nares Strait and to the Atlantic Ocean through the Davis Strait and Labrador Sea. Belonging to the High Arctic region, mean air temperatures in Baffin Bay are below 5°C year-round. In winter (December to April), mean air temperature is approximately -20°C, and water temperature at the surface is below -1°C. In summer (July to September), air temperature closely resembles the surface water temperature of

about 4°C but can reach 10°C or higher in coastal areas (Valeur et al., 1996). Precipitation in the Baffin Bay region is generally low (~250 mm yr⁻¹), due to the low moisture content of the cold air and falls mostly as snow in summer and fall. Winds are closely related to pressure gradients and typically blow from the northwest in the winter, and from the southeast in the summer (Valeur et al., 1996). The general circulation pattern of ocean currents in Baffin Bay is made up of the West Greenland Current (WGC), a weak but relatively warm northward-flowing current along the western coast of Greenland, and the Baffin Island Current (BIC), a stronger cold southward-flowing current along the east coast of Baffin Island, which carries sea ice and icebergs south to the Labrador Sea (Münchow et al., 2014). Sea ice begins to form in Baffin Bay in September and reaches a maximum in March, which covers the entire bay except for the Davis Strait. Throughout the ice season, more sea ice is found on the western side of Baffin Bay due to the relatively warm WGC. Ice cover starts to decrease in April and by September conditions are generally ice-free (Tang et al., 2004). Icebergs are found throughout the Baffin Bay region, with the greatest concentrations within 50 km of the Greenland coast. Long-term iceberg motion is characterized by short periods of drift that can reach speeds of 10 to 30 km d⁻¹, and long periods of grounding and entrapment in coastal areas (Tang et al., 2004). Iceberg drift studies in Baffin Bay have indicated that icebergs move erratically with drift speeds that rarely exceed 17 km d⁻¹ (Valeur et al., 1996).

1.3.2 Labrador Sea

The Labrador Sea is a relatively cold and fresh basin of the subpolar North Atlantic, which connects to Baffin Bay through the Davis Strait. Surface water temperatures vary between -1°C in winter and 5-6 °C in summer. South of the Grand Banks, water temperatures can range from near freezing (-1.7°C) in the Labrador Current to 20°C or more in the Gulf Stream (Yashayaev, 2007). The pattern of ocean currents in the Labrador Sea is counter clockwise and consists of the WGC, which carries warmer, more saline waters northwards along the Greenland coast and the Labrador Current (LC), which brings cold, relatively fresh waters from the BIC southwards along the Labrador coast. The main Labrador Current is made up of two branches. The more powerful offshore branch flows southward along the eastern edge of the Grand Banks and moves sea ice and icebergs toward the much warmer waters of the Gulf Stream (Petrie & Isenor, 1985). The weaker inshore branch flows towards the eastern coast Newfoundland and has the potential to

cause hazardous shipping conditions as icebergs are carried towards transatlantic shipping lanes near the Grand Banks of Newfoundland. Sea ice typically starts forming along the Labrador Coast in December, reaching its maximum extent by late February, and is typically ice-free by late June to early July (Carrieres, 2000). From northern Baffin Bay to southern Labrador Sea, the long-term average sea ice motion follows the coast at approximately 10-15 km d⁻¹ (Valeur et al., 1996). Variations in wind speed and sea-ice cover can influence this motion or stop it entirely for short periods. Icebergs can be carried by the cold waters of the Labrador Current as far south as 41°N latitude but will typically melt rapidly once they encounter the warm temperatures of the Gulf Stream. The severity of the iceberg season on the Grand Banks is strongly correlated with variations in air temperature, sea-ice conditions, and ocean temperatures along the Labrador Coast (Cyr et al., 2021).



Figure 1.1: Study area of interest and main currents influencing iceberg drift from West Greenland glaciers to the Grand Banks of Newfoundland (area delineated by the dashed line) (ECCC, 2019a).

Chapter 2: Background

2.1 Iceberg morphology

An iceberg is defined by the Manual of Standard Procedures for Observing and Reporting Ice Conditions (MANICE; Canadian Ice Service, 2005) as “*A massive piece of ice of greatly varying shape, protruding 5 m or more above sea level, which has broken away from a glacier and which may be afloat or aground*”. The size of an iceberg is largely dependent on the characteristics of the glacier or ice shelf from which the iceberg calved and the length of time it has been deteriorating. Iceberg size classifications, and those of their smaller derivatives, are based on the length of the iceberg along its waterline and its height above the sea surface and can be categorized as: growlers, bergy bit, small, medium, large, and very large (Table 2.1). Iceberg morphology is commonly described in terms of sail and keel, which are used to identify the above- and below-water portions of the iceberg, respectively (Canadian Ice Service, 2005).

While the variety and complexity of iceberg shapes often makes them difficult to classify, the CIS categorizes icebergs into several common shapes, including tabular, domed, pinnacle, wedge, drydock or blocky (Table 2.2). Tabular icebergs are characterized by a flat top and steep sides, often with horizontal banding and a length-to-height ratio greater than 5:1. Domed icebergs are smooth and rounded on top. Pinnacle icebergs typically have one or more spires or pyramids. Wedged icebergs are flat on top and with steep vertical sides on one end and sloping on the other end. Drydocked icebergs have eroded such that a U-shaped slot is formed near or at water level, with twin columns or pinnacles on either side. Blocky icebergs are also flat-topped with steep vertical sides but have a shorter length-to-height ratio than tabular icebergs (Canadian Ice Service, 2005). If no other description applies, the iceberg is simply referred to as a non-tabular. The average height to draft ratios of each iceberg shape are listed in Table 2.2.

Table 2.1: Iceberg size classifications from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (Canadian Ice Service, 2005).

Size	Height above sea surface (m)	Length (m)	Weight (Mt)
Growler	<1	<5	0.001
Bergy Bit	1-5	5-15	0.01
Small	5-15	15-60	0.1
Medium	16-45	61-120	2.0
Large	46-75	121-200	10.0
Very Large	>75	>200	>10.0

Table 2.2: Average iceberg height to draft ratios from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (Canadian Ice Service, 2005).

Shape	Height to Draft Ratio
Tabular	1:5
Non-tabular	1:5
Domed	1:4
Pinnacle	1:2
Wedge	1:5
Drydock	1:1
Blocky	1:5
Ice Island	-

2.2 Iceberg production

Icebergs are produced when ice breaks free from a glacier or an ice shelf and floats freely in the ocean. This process is called calving. It has been estimated that 90% of all icebergs drifting in Baffin Bay and the Labrador Sea originate from glaciers descending to sea level on the western Greenland coast (ECCC, 2019a). The majority of the remainder come from glaciers flowing from the east coast of Ellesmere and Devon islands in the Canadian Arctic (Van Wychen et al., 2014). The total annual production of icebergs in Baffin Bay is estimated to be 10,000 to 40,000 (ECCC, 2019a). Once an iceberg calves, there is a low likelihood that it will reach the Grand Banks of Newfoundland, but potentially very high economic and environmental repercussions if it does. For example, the consequences of an iceberg impact with a fixed or floating oil platform could be severe, not only in terms of the structural integrity of the installation, but also the health and safety

of workers, and the environment (Fuglem & Jordaan, 2017). Of the estimated 10,000 to 40,000 icebergs that are produced annually, on average only 492 icebergs manage to cross 48°N latitude and enter the zone where they become a risk to transatlantic shipping, although this number varies considerably from year to year (Figure 2.1; IIP, 2018).

These iceberg hazards are actively monitored by the International Ice Patrol (IIP; <https://www.navcen.uscg.gov/?pageName=IIPHome>), whose mission is to eliminate the risk of iceberg collisions in the North Atlantic Ocean. This is accomplished primarily through aerial ice reconnaissance flights during the spring and summer iceberg season. The intensity of iceberg seasons observed by the IIP can vary dramatically between years. For example, during the 2018 iceberg season, only 208 icebergs crossed south of 48°N, while the 2019 iceberg season saw 1515 icebergs cross 48°N, making it the 10th most severe iceberg season in the IIP’s entire iceberg data record since 1900 (IIP, 2019). Icebergs passing south of 48° N (Figure 2.1) are most frequently observed in the late winter and spring (March to June), less frequently in the months of February, July, and August, and infrequently in the fall and early winter (September to January) (Figure 2.1).

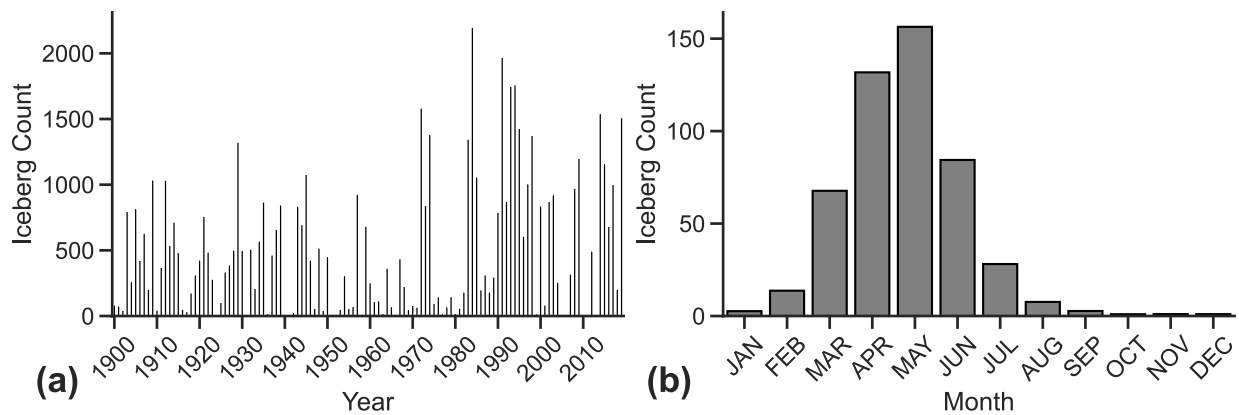


Figure 2.1: Bar plots of: (a) annual count and (b) monthly averages of icebergs crossing south of 48°N latitude between 1900-2020 (IIP, 2020).

2.2.1 Greenland

Iceberg calving represents a major component of the total mass balance of the Greenland Ice Sheet (GIS), with an average total ice discharge of $537.4 \pm 4.6 \text{ Gt a}^{-1}$ between 2010 and 2018 (Bigg et al., 2018). Over 100 tidewater glaciers drain from west Greenland, which discharged, on average, $255.2 \pm 0.8 \text{ Gt a}^{-1}$ of ice from 2010 to 2018 (Mouginot et al., 2019). The majority of active

glaciers are located between Smith Sound and Disko Bay (Figure 2.2), though in Nares Strait, both the Humboldt and Petermann glaciers can represent significant sources of periodic discharge ($6.4 \pm 1.3 \text{ Gt a}^{-1}$ and $11.7 \pm 1.2 \text{ Gt a}^{-1}$ in 2018, respectively) (Mouginot et al., 2019). The largest source of iceberg production is from Melville Bay, between Cape York to Upernavik, where it is estimated that over 10,000 icebergs are produced annually. A second area of importance are the Karrat and Umanak Fjords, where approximately 5,000 to 8,000 icebergs are calved each year from several major glaciers. Disko Bay also produces a significant number of icebergs, with Jakobshavn Glacier accounting for 45% of discharge, followed by 32% from Store Glacier and Rink Glacier. Although iceberg production in Greenland tends to vary little from year to year, icebergs produced by calving can vary greatly in size, from growlers and bergy bits to very large icebergs, and ice islands (large tabular icebergs greater than 1 kilometre in length) (Mouginot et al., 2019; Valeur et al., 1996).

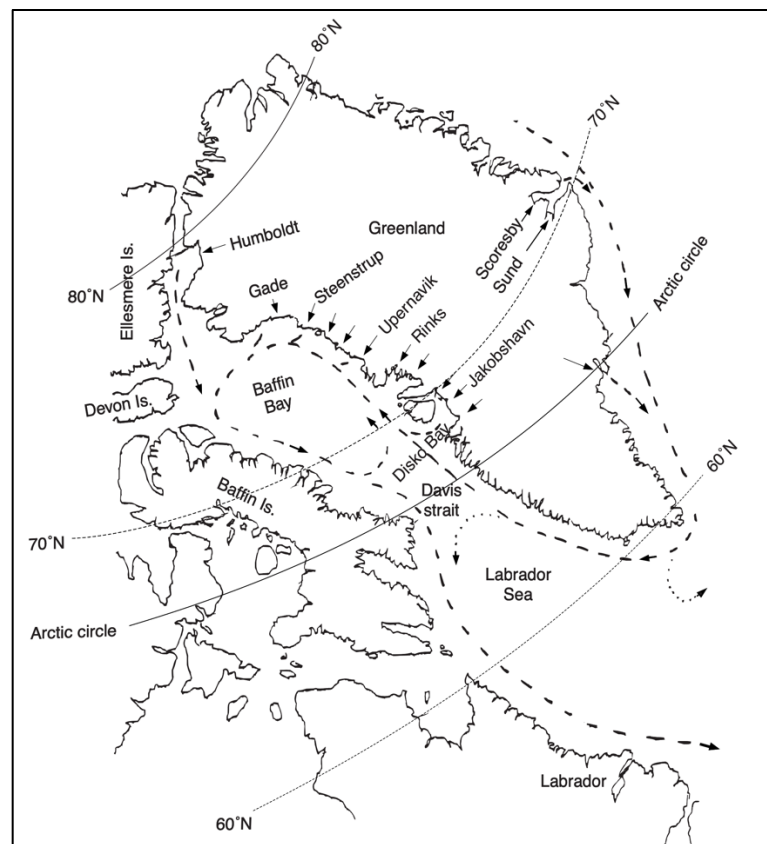


Figure 2.2: Map of major sources of Greenland iceberg production and drift paths of icebergs (Diemand, 2001).

2.2.2 *Canadian Arctic*

In the Canadian Arctic Archipelago (CAA), the primary sources of iceberg production are marine-terminating outlet glaciers of the Queen Elizabeth Islands (QEI) (Wyche et al., 2021). The glaciated regions of the QEI, consisting of Ellesmere Island, Axel Heiberg Island and Devon Island, contain $\sim 104,000 \text{ km}^2$ of ice (Figure 2.3), which represents 25% of Arctic glacier ice outside the Greenland Ice Sheet. The Prince of Wales Icefield is the largest contributor to iceberg fluxes, with Trinity and Wykeham glaciers flowing from it accounting for 62% of the total discharge of icebergs to the ocean in the CAA in 2016 (Dalton et al., 2019). The Devon Ice Cap is the next largest contributor to iceberg flux, with Belcher Glacier accounting for 42% of total iceberg discharge from that island (Van Wyche et al., 2012). The Agassiz Ice Cap is also a contributor to iceberg fluxes, with 54% of calving occurring from Eugenie Glacier (Williamson et al., 2008). Other glaciers and ice caps in the QEI, such as Manson Icefield and Sydkap Ice Cap are minor sources of iceberg fluxes for Baffin Bay, although Northern Ellesmere Icefield can discharge significant volumes of icebergs to the Arctic Ocean, particularly after glacier and ice shelf breakup events (Mueller et al., 2017; White & Copland, 2019). Van Wyche et al. (2021) estimated the total ice discharge via calving in the QEI to be $3.203 \pm 0.554 \text{ Gt a}^{-1}$ in 2019/2020. However, annual iceberg calving rates can be highly variable due to changes in tidewater glacier dynamics, such as the initiation of surges that can drastically change the rate at which ice is transported to the ocean (Van Wyche et al., 2016; Wyche et al., 2021).

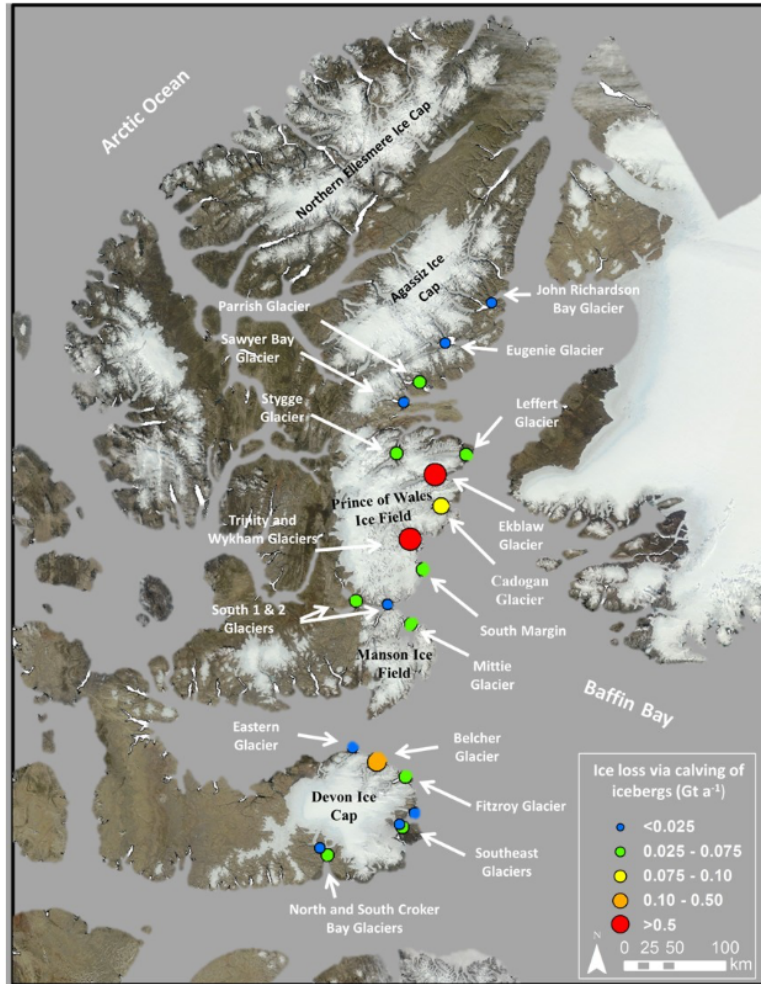


Figure 2.3: Locations and rates of iceberg production in the Queen Elizabeth Islands (QEI) for 2012 (Mueller et al., 2013).

2.3 Iceberg drift

2.3.1 Factors influencing drift

The path of a drifting iceberg is primarily influenced by currents, winds, and the Coriolis force. Wolford (1982) identified four main factors that determine how many icebergs will survive to make it to the Grand Banks: 1) annual iceberg production; 2) prevailing environmental conditions as the iceberg drifts free of its source fjord; 3) meteorological and oceanographic conditions during its transit through Baffin Bay and the Labrador Sea; and 4) the rate of deterioration as it drifts southwards. By the time surviving icebergs reach the Grand Banks, a journey that can take eight months or longer from their source, they will have lost at least 85% of their original mass (Murray, 1969).

The system of ocean currents in Baffin Bay, Davis Strait and Labrador Sea is the major transport mechanism responsible for moving icebergs southward from Baffin Bay to the Grand Banks (Cheema & Ahuja, 1978) (Figure 1.1). While slower than the wind, these currents act on a much larger submerged portion of the iceberg than the subaerial portion exposed to the wind, which can vary markedly between icebergs and influence drift (Savage, 2001a). Three primary transport pathways were identified by Marko et al. (1994). One follows the weaker, northerly branch of the WGC into northern Baffin Bay before turning westward and following the Baffin and Labrador currents southward. A second follows the WGC northward to Davis Strait before moving west to join the southerly Baffin and Labrador current flow. The third pathway encompasses all icebergs that have moved offshore beyond the strong, narrow current regimes overlying the continental shelf edges. During the fall and winter, icebergs trapped in pack ice will tend to drift southward with the sea ice at speeds of 5 to 20 km d⁻¹ (Marko et al., 1982).

While drifting in Baffin Bay, icebergs can be locked into landfast and pack sea ice for substantial periods of the year. When the sea ice breaks up during the brief summer open water season, the icebergs can move more freely and drift out of Baffin Bay and into the open ocean of the North Atlantic via the Labrador Current (Figure 2.2) (Münchow et al., 2014). It is possible for icebergs moving southward in these currents to meet their demise by drifting eastward into the comparatively warmer ice-free water of the Labrador Sea and deteriorating, or by drifting westward and becoming trapped in the many bays and shoal areas along the coast (Wolford, 1982). The southern limit of iceberg drift is generally defined by the northern edge of the warm North Atlantic Current, between 40°N to 51°N (El-Tahan et al., 1987).

The influence of wind on iceberg drift is typically small in comparison to the effect of ocean currents, although high winds persisting over an extended period can have a pronounced effect on drift trajectory. The wind causes drag on the exposed surface of the iceberg, which is directly related to its shape above the waterline (White et al., 1980), and this force can directly affect the path that a drifting iceberg follows and drive the iceberg at a different velocity than the surrounding water currents. Sea ice can also modify the wind forces on icebergs in closely packed ice by hindering the formation of wind-driven currents (Wolford, 1982). Throughout Baffin Bay, wind velocity is to a large extent related to the position and intensity of the Icelandic Low, the atmospheric circulation pattern responsible for transporting icebergs out from West Greenland fjords, across Baffin Bay and southward along the Labrador Coast (Wolford, 1982). The Icelandic

Low, therefore, can play an important role in determining the severity of the iceberg season off the coast of Newfoundland.

2.3.2 Iceberg drift tracking

The ability to reliably track icebergs is of interest to university researchers, government agencies and the Arctic offshore oil and gas industry. Existing monitoring strategies include the use of optical satellite imagery to produce high-resolution images of icebergs that can be used for tracking; however, optical sensors are unable to penetrate cloud cover and are dependent on solar illumination. Synthetic aperture radar (SAR) satellite imagery is the preferred data source for operational ice centers responsible for providing information on iceberg occurrences, as it is unaffected by cloud cover and daylight (Lane et al., 2004; McCandless & Jackson, 2004). Yet, SAR imagery often has limited spatial and temporal coverage, as well sensor limitations that can hinder the detection of small icebergs. As a result, it is often necessary to supplement remote sensing data with *in-situ* measurements obtained from ice drift tracking beacons.

Tracking beacons have been used to measure the movements of ice in the Arctic for the past several decades (e.g., Olenicoff, 1973; Brown and Kerut, 1978; IIP, 2011, 2013; Peterson and Prinsenberg, 2014). Previous studies have used beacons to provide drift data for testing iceberg and sea-ice drift models, validating drift tracks derived from satellite imagery, and testing algorithms for identifying icebergs and ice island fragments in SAR imagery. Beacons can also locate and help to better understand the long- and short-term movement of hazardous ice features, provide a valuable additional source of information for shipping operations in polar waters, and mitigate the risk hazards for operations in ice-infested waters (Peterson et al., 2009).

Recent beacon technologies used for iceberg drift tracking rely on Global Navigation Satellite Systems (GNSS) and provide a positional accuracy of approximately 2 m. Data telemetry is achieved using the Iridium satellite network, which offers excellent coverage over the polar regions, and provides bi-directional data transmission in near real-time. The most popular commercial tracking systems are made by MetOcean and include the Compact Air-Launched Ice Beacon (CALIB) and Polar Surface Velocity Program (SVP) drifter buoy. The CALIB can be deployed from a fixed-wing aircraft and is currently in use by the CIS to instrument icebergs and ice islands in the Canadian Arctic. The Polar SVP is a hand deployable drifter buoy with meteorological and oceanographic measurement capabilities, which after having become

dislodged from an iceberg, can continue to function while floating and help to fill the gap in atmospheric observations for weather forecasters and modellers. Recently, several studies (e.g., Carlson et al., 2017, 2020) have also explored the use of low-cost, open-source technologies to study the drift of icebergs. The success of these studies has demonstrated that such technology is a reliable, and cost-effective method of monitoring iceberg drift in the Arctic.

2.4 Iceberg deterioration

Iceberg drift trajectories are strongly dependent on the physical and morphological properties of the iceberg, so as an iceberg decays, the forces acting on it evolve (Wagner et al., 2017). Therefore, knowledge of the deterioration of an iceberg is essential for forecasting its drift. The most important mechanisms of iceberg deterioration were identified by Job (1978) and later summarized by Savage (2001b). They are: 1) melting of the exposed iceberg surface by solar radiation; 2) buoyancy-induced natural convection along the submerged sides of the iceberg, and to a lesser extent along the bottom; 3) forced convection melting of the submerged portions due to differential velocity between the iceberg and surrounding fluids; 4) waterline wave erosion and undercutting; 5) calving of the ice overhang caused by wave erosion; 6) subsurface calving due to upthrust of underwater rams formed by other melting mechanisms; 7) convection caused by wallowing or overturning; 8) differential melting along cracks and faults in the iceberg leading to further calving, and 9) fracture of the ice due to internal stresses. It is extremely difficult to obtain accurate estimates of items 6, 8 and 9 due to the lack of quantitative theories and uncertainties in geometry and shape effects, and lack of observations, while item 7 is not believed to be significant as icebergs typically spend little time in wallowing or overturning states (El-Tahan et al., 1987). The first five deterioration mechanisms are described in more detail below.

2.4.1 Surface melting due to solar radiation

Due to the high density and thermal conductivity of seawater, and because most of an iceberg's mass is found below the water, the majority of melt takes place on its submerged surfaces (El-Tahan et al., 1987). However, solar radiation absorbed by the exposed iceberg surface represents a minor but steady source of ablation (White et al., 1980). Despite fog and cloud cover reducing the ratio of received radiation by up to 40%, solar insolation can be a significant contributor to melt, especially in the summer months. The amount of absorbed solar radiation is

strongly sensitive to the albedo of the iceberg surface, which varies according to the surface roughness, incidence angle with the sun, amount of snow or frost cover and the presence of surface sediments. Measured values of ice albedo vary from less than 0.1 for clear ice surfaces to 0.95 for fresh snow (Kubat et al., 2007). A reasonable albedo of 0.7 for icebergs is suggested by Savage (2001b), however this value may vary, as shown by Crawford et al. (2015), who measured an iceberg albedo of 0.56 in Baffin Bay. Solar radiation may also have a significant effect on calving through the creation of melt pools that generate thermal stresses in the surface layer of the iceberg (Figure 2.4).

2.4.2 *Melting due to buoyant vertical convection*

As an iceberg melts in seawater, the melting process produces both cooling and dilution of the adjacent water layer (Figure 2.4). This water is lower in salinity and density and tends to rise against the surrounding seawater. At the same time, the colder, more saline water further away from the iceberg is heavier than the warmer more distant water and tends to sink. These resulting thermal and salinity gradients can induce currents that allow for the convection of heat from the water to the iceberg surface, promoting melt of the submerged portion of the iceberg (Savage, 2001a).

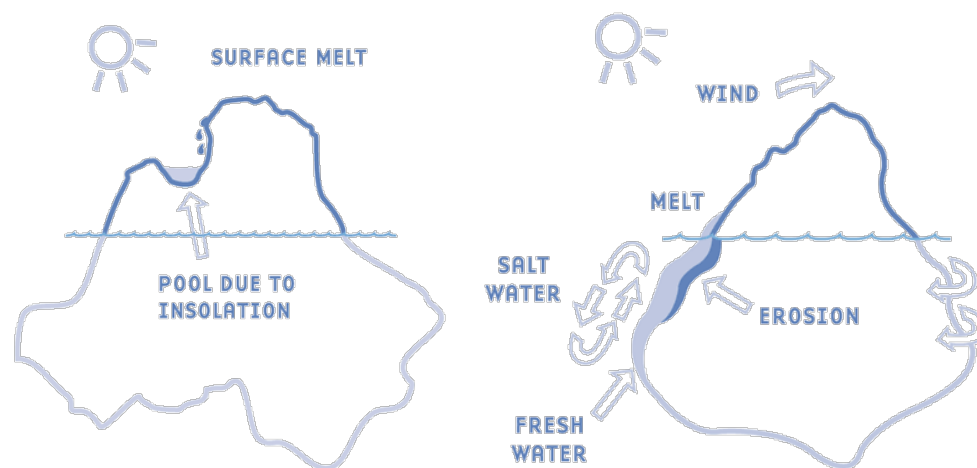


Figure 2.4: Mechanisms of iceberg deterioration: (left) melting due to solar radiation and (right) buoyant vertical convection (ECCC, 2019a).

2.4.3 *Melting due to forced convection*

Strong prevailing Arctic winds can cause iceberg deterioration in two ways. As a rule of thumb, icebergs drift at ~2% of the wind speed (Wagner et al., 2017), so winds can drive the

iceberg through the water at velocities of 9 to 26 km d⁻¹ relative to the surrounding water currents (El-Tahan et al., 1987). The relative motion of the water past the iceberg generates turbulence that carries heat to the surface of the submerged portion of the iceberg (Figure 2.4). The melting rates from forced water convection are significantly larger than those from natural buoyant convection (Bigg et al., 1997). When the wind speeds are negligible, the iceberg drifts with the water current and little-to-no melting from forced water convection occurs. Second, winds can contribute to the melting of the exposed surface of the iceberg above the waterline directly by forced air convection. However, the surface melt rate due to forced air convection is comparable to the melt rate due to solar radiation and overall, is very small compared to forced water convection (Savage, 2001a).

2.4.4 Wave erosion

Wave erosion at the waterline of an iceberg is the predominant influence on iceberg deterioration (Kubat et al., 2007). Wave action is a very efficient way of dissipating the cooling effect of an iceberg and providing a supply of warmer water at the iceberg waterline. The basic heat transfer mechanisms are like those of forced water convection described above. However, the larger water velocities associated with wave motion result in enhanced heat transfer and increased melting in the region near the ocean surface (Figure 2.5). Even in cold waters waves can rapidly erode a notch or ledge into the side of an iceberg, after which calving or fracture can occur (White et al., 1980).

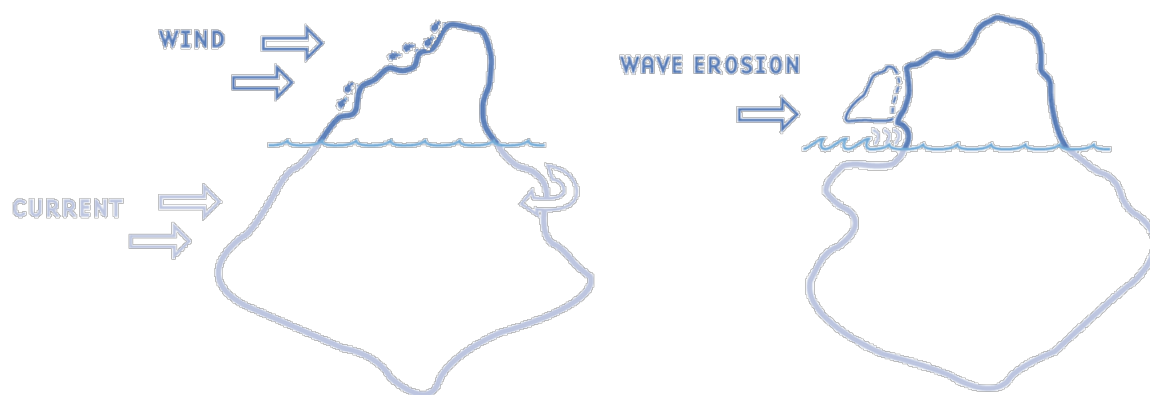


Figure 2.5: Mechanisms of iceberg deterioration: (left) Forced convection of wind and water currents and (right) wave erosion creating a wave notch and subsequent calving of an overhanging slab (ECCC, 2019a).

2.4.5 *Calving*

The major calving mechanism of icebergs is a result of the wave erosion described in the previous subsection. As wave erosion progressively cuts rounded notches in the iceberg, the notches become deeper and a protruding overhang above the waterline develops (Figure 2.5). The overhanging slab acts as a cantilever beam with the weight of the overhanging ice, with tensile bending stresses developing on the upper portion of the slab and compressive bending stresses occurring in the lower portion (Savage, 2001a). Eventually, a critical length is reached and the stresses due to the weight of the overhang will cause the calving of the slab. The time required for the overhanging slab to calve decreases significantly as wave height increases and the wave period decreases (El-Tahan et al., 1987). A second calving mechanism, known as the "footloose mechanism", may also produce calving from the submerged portion of the iceberg. This occurs when rapid waterline erosion and subaerial cliff calving lead to a protruding underwater ram and the resulting buoyancy stresses are sufficient to break off significant pieces from the iceberg (Wagner et al., 2017; White et al., 1980).

2.5 **Iceberg drift and deterioration modelling**

2.5.1 *Modelling iceberg drift*

There are essentially three types of approaches that have been used for the modelling of iceberg drift: statistical, kinematic and dynamical models. The relative merits of each are reviewed by Marko et al. (1988), and later compared by Andersson et al. (2018). Here, statistical and kinematic models are briefly touched upon, with more emphasis given to the dynamical models, which is the type of model used in this study.

Statistical models (e.g., Andersson et al., 2016, 2018; De Margerie, 1986; Gaskill & Rochester, 1984) combine an iceberg's last known position with statistical properties of previous trajectories to estimate a probability distribution of the iceberg's future position and velocity (Smith, 1993). The underlying dynamics of iceberg motion are usually ignored. Some statistical models may incorporate deterministic effects using environmental data such as tides and winds (Smith & Donaldson, 1987). According to Marko et al. (1988), statistical models can exhibit superior performance for short-term iceberg drift forecasts when compared to conventional dynamical models.

Kinematic models (e.g., Cheema & Ahuja, 1978; Garrett, 1985; Gaskill & Rochester, 1984)

estimate drift using empirical relationships with other parameters. A simple example is the rule-of-thumb that icebergs drift relative to the ocean current at 2% of the wind speed (Garrett et al., 1985). Movement predictions are derived from previous portions of iceberg tracks or from observed movements of other icebergs (Marko et al., 1988). Kinematic models also ignore iceberg dynamics but include the major driving forces for iceberg movements, including water drag, air drag, and the effects of Coriolis force. Elements of kinematic models can be added to either statistical or dynamical models (Smith & Donaldson, 1987). Both statistical and kinematic approaches have also been applied in situations where the requirements of a dynamical model could not be met due to a paucity of environmental data (Marko et al., 1988).

Dynamical models (Andersson et al., 2017; Bigg et al., 1997; Eik, 2009; El-Tahan et al., 1987; Kubat et al., 2005; Turnbull et al., 2015) consider the various driving and resisting forces acting on an iceberg of a known mass and integrate Newton's equations of motion to obtain the iceberg's velocity and position as a function of time (Savage, 2001a). The equation of motion for an iceberg can be expressed as:

$$m \left(\frac{dV}{dt} + f \times V \right) = F_a + F_w + F_r + F_p + F_{am} \quad (1)$$

where m and V are the mass and velocity of the iceberg, respectively, and f is the Coriolis force parameter. The terms on the right-hand side of Eq. 1 correspond to the forces acting on the iceberg, where F_a is the air drag on the above-water portion of the iceberg, F_w is the water drag on the underwater portion of the iceberg, F_r is the force due to wave radiation stress, F_p is the horizontal pressure gradient force, and F_{am} is the force associated with the added mass of the iceberg. Equations describing these forces are provided in detail in Kubat et al. (2005) and described briefly below.

The force due to air drag a F_a , is given by:

$$F_a = \frac{1}{2} \rho_a C_a A_a |V_a| V_a \quad (2)$$

where ρ_a is the air density, C_a is air drag coefficient, A_a is the cross-sectional sail area and V_a is wind velocity. Because iceberg velocity is usually much smaller than wind velocity, the value of the relative velocity is replaced with wind velocity in Eq. 2.

The force due to water drag, F_w , is calculated as follows:

$$F_w = \frac{1}{2} \rho_w C_w \sum_k A_w(k) |u_w(k) - V| (u_w(k) - V) \quad (3)$$

where ρ_w is water density, C_w is the water drag coefficient. The keel is divided into 10 m depth layers. The k th layer has an area A_w . Water current acting on that layer is $u_w(k)$. The drag coefficient, C_w is assumed to be the same for each layer.

The force due to wave radiation stress, F_r is calculated as follows:

$$F_r = \frac{1}{2} \rho_w C_{wf} g L a^2 |V_a| V_a \quad (4)$$

where C_{wf} is the wave force coefficient, g is the gravitational acceleration, L is the waterline length of the iceberg, and a is wave amplitude. This equation is used operationally to calculate forces due to wind waves and swell waves (Kubat et al., 2005). For wind waves, force direction is assumed to coincide with wind direction. For swell waves, the direction is provided as an input to the model.

In general, dynamical models require a detailed specification of iceberg mass and surface area, as well as all significant forces acting on the iceberg, both in terms of physical parameters and the atmospheric, water, and rotating Earth environments (Smith & Donaldson, 1987). While there are uncertainties associated with the various forcing terms in the equations of motion, as the values of these coefficients are refined, the prediction skill of the model improves. It is also possible to combine dynamical models with iceberg deterioration models of various levels of sophistication. It is for this reason that dynamical models are regarded as the most appropriate type for detailed forecasting (Savage, 2001a). This is evidenced by the fact that dynamical models are used operationally by the CIS, NRC and IIP (Murphy & Carrieres, 2010).

2.5.2 Modelling iceberg deterioration

Several deterioration models have been described in the literature (El-Tahan et al., 1987; Kubat et al., 2007; Savage, 2001b) that are aimed at complementing drift models. Due to the complexity of the many environmental conditions that influence iceberg deterioration, such as wind, water currents, waves, air and water temperatures, deterioration processes are usually modelled through semi-empirical parameterizations (Kubat et al., 2007). An early study by White et al. (1980) developed methods for estimating deterioration rates due to various processes. These

methods became the basis for many subsequent deterioration models, including the current operational iceberg deterioration model employed by the CIS (Kubat et al., 2007).

El-Tahan et al. (1987) compared the estimates of White et al. (1980) with field measurements to examine the relative importance of the various deterioration mechanisms on icebergs off the coast of Newfoundland and Labrador. The results of Table 2.3 show that wave effects, including erosion and the resulting calving of overhanging slabs, were the dominant deterioration mechanisms. Together, these mechanisms accounted for more than 80% of the observed deterioration. Forced convection contributed to approximately 16% of the deterioration rate, while only 2% was found to be caused by buoyant convection. The wind convection and solar radiation contributions to the daily melt rate were each less than 0.5%. It was also found that the size and shape of the iceberg had significant effects on deterioration rates. For example, small, non-tabular icebergs drifting on the Grand Banks during July to November completely disintegrate in less than three days, while growlers can vanish in less than a single day in any month of the year (Savage, 2001a).

Table 2.3: Average contributions of iceberg deterioration mechanisms to mass loss. Based on studies of icebergs off the coast of Newfoundland and Labrador (El-Tahan et al., 1987).

Deterioration mechanism	Contribution to total loss (%)
Solar radiation	0.3 - 5.3
Buoyant convection	1.2 - 1.5
Wind convection	0.3 - 2.9
Forced convection (water)	11.6 - 27.8
Wave erosion	50.6 - 65.5
Wave induced calving	19.0 - 21.0

2.5.3 *Model temporal and spatial scales*

Iceberg forecast models can also be classified according to the temporal and spatial scales over which they are designed to operate. Short-term models are most frequently used to provide forecasts of iceberg trajectories for periods of up to approximately one day. These models are centered on a fixed position and typically extend to 30 km. One of the most common applications of these models is to provide information for iceberg management operations (Marko et al., 1988).

Intermediate-term or regional models provide extended forecasts for periods of up to several (3-14) days. The area of interest and data acquisition for intermediate models is much greater, extending over distances of several hundred kilometres. Due to the larger areal extent involved and the corresponding increase in the number of icebergs, the model may provide forecasts of groups rather than the locations of individual icebergs. Applications for the intermediate-scale iceberg models include forecasts for oil and gas drilling platforms, advisories for shipping, and inputs to the planning of large-scale aerial iceberg surveillance programs conducted by the IIP (Marko et al., 1988). Long-term models are used when information about iceberg parameters is required for periods of up to several months. Given the limitations of atmospheric and oceanic forecasting capabilities, the products of such models are typically limited in detail when compared to the outputs of shorter-term models. Predictions are usually expressed as estimates of regional iceberg numbers, or the "severity" of iceberg hazards likely to be encountered. The output of these models can be applied to operational planning and provide estimates of the feasibility and expected costs of offshore activities, such as hydrocarbon resource exploitation and marine transportation (Marko et al., 1988).

2.5.4 *Determining drift model skill*

Previous studies have used several methods of quantifying the performance of an iceberg drift model (e.g., Allison et al., 2014; Andersson et al., 2018; Keghouche et al., 2009; Kubat et al., 2005; Murphy & Carrieres, 2010). Model performance is commonly assessed through quantified comparisons of the distance error, which is defined as the calculated great circle distance between modelled and observed iceberg positions at a given time step (Mongroo & Li, 2010). The scaled distance error, which is defined as the distance error divided by the length of the observed drift track at a given point in time, can provide an indication of the magnitude of model error as a function of the observed and modelled distance travelled by the iceberg. The root-mean-square error (RMSE) distance can be calculated for all iceberg forecasts to assess average model-prediction error. A lower RMSE over a large set of forecasts indicates that the modelled positions more closely resemble the observed positions. The RMSE is described by the formula:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (\Delta X_i)^2} \quad (5)$$

where N is the number of forecasts, and ΔX_i is the linear distance between the observed and forecast iceberg positions measured in kilometres (Willmott & Matsuura, 2005).

To determine whether a model is over or under-forecasting the total distance travelled by an iceberg during the forecast period, the cumulative distance error and final distance error can be calculated. The cumulative distance error is the sum of total distance travelled by the observed and modelled iceberg tracks. The final distance error is the difference between the magnitudes of the observed and modelled displacements, both measured with respect to the initial observed position (Ballicater, 2013). For those drift trajectories with highly linear behaviour, the cumulative distance error and final distance error values will be equal, however *in-situ* observations often indicate that many drift tracks are highly non-linear.

As the measures of error distance described above only take into consideration the vector magnitude of the difference between observed and modelled positions, it is often also necessary to consider the accuracy of the modelled direction. The directional error is measured by calculating the absolute difference between the angle of the modelled position and the angle of the observed position, both measured clockwise from North and with respect to the initial observed position. The directional error aids in determining whether forecasts with large error distances are the result of over or under forecasting distance, or the result of inaccurately forecasting direction.

2.5.5 Sensitivity analysis

Another tool that can be used to assess model performance is a sensitivity analysis, which is the process of determining how changes in model input parameters affect the modelled outputs (Bokulich & Oreskes, 2017; Wainwright & Mulligan, 2004). In most sensitivity analyses, a single parameter is varied incrementally, while keeping all other parameters unchanged. The modelled outputs are assessed in response to these changes and the sensitivity of the model is expressed as a proportional change in the model output per unit change in the model input. Sensitivity analyses can provide valuable insight of which parameters explain the greatest variability of the metric used to measure model skill and can assist with model calibration, which is the process of assigning input parameters values by maximizing the model fit to observations, with the aim of improving overall model performance.

2.5.6 *Operational iceberg drift and deterioration modelling*

The CIS operational iceberg model was originally developed in the 1980s by the IIP (Mountain, 1980). However, in response to increased offshore oil and gas exploration activities in the Grand Banks, the development of a new model was undertaken (Carrieres et al., 2001). The primary goals of this new model were to improve the quality of forecasts and provide information on the uncertainty in iceberg forecasts by incorporating up to date physics of iceberg drift and deterioration, taking advantage of ocean current predictions from coupled ice-ocean models and tracking the drift and deterioration of small ice pieces produced by iceberg calving events (Kubat et al., 2007). The model was developed by the NRC in the late 1990s and implemented at the CIS as the NAIS operational iceberg drift model (Kubat et al., 2005, 2007).

The NAIS iceberg drift model is a comprehensive iceberg drift and deterioration model used operationally by the CIS to forecast iceberg conditions along the east coast of Canada. A major advantage of the NAIS model over the model used by the IIP is its ability to use the new generation of high-resolution ocean current models. Versions of the model have also been adapted for use by offshore operators in the Grand Banks to provide information for iceberg management operations (Sudom et al., 2014). The model is run automatically every 6 hours to keep the distribution of icebergs up to date, and iceberg analysis charts with this information are made available daily (Figure 2.6) (ECCC, 2019b). Advantages of the iceberg model include the ability to accept a wide variety of ocean current data, as well as accepting new iceberg size and shape data as they become available.

The NRC continues to develop and enhance the NAIS iceberg drift model to forecast the drift path of icebergs more accurately and to improve the quality of iceberg forecasts and ensure safe and efficient marine operations in Canadian waters. In response to end-user interest, NRC has developed a version of the NAIS iceberg drift model that can be operated directly in stand-alone mode, without a link to the CIS. This allows end-users the ability to input iceberg and environmental data into the model to produce output about iceberg drift whenever needed. The stand-alone version of the model was also translated from its original programming language, Fortran, to the more modern Python programming language to allow for wider dissemination of the code.

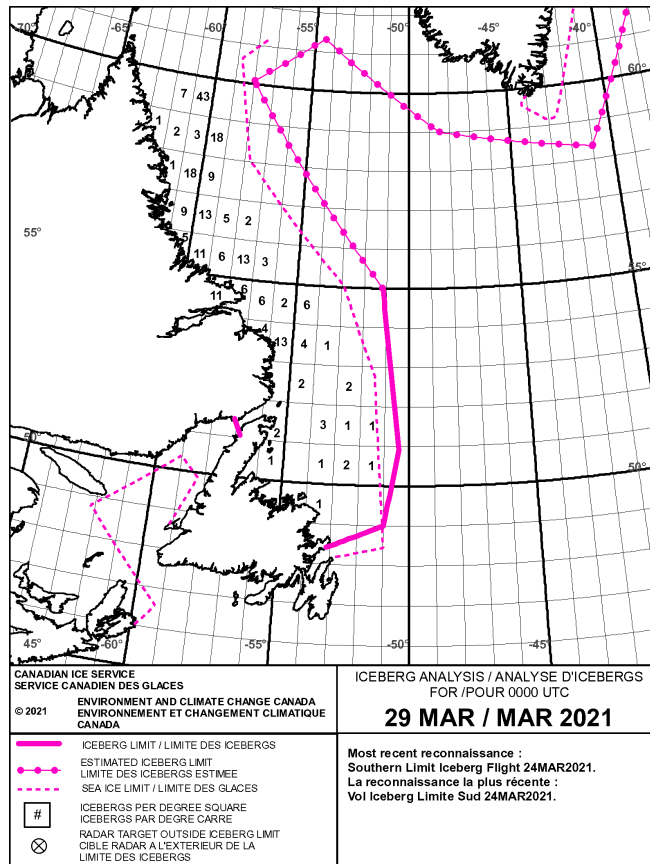


Figure 2.6: Example of a daily iceberg analysis chart produced by the North American Ice Service (NAIS) iceberg drift model (ECCC, 2019b).

Chapter 3: Datasets and Methodology

To meet the objectives of this study, a wide range of model input data, consisting of *in-situ* iceberg measurements, modelled environmental driving forces and remote sensing data were used to perform a comprehensive assessment of the hindcasting performance of the NAIS iceberg drift model.

3.1 Iceberg drift tracking beacons

To facilitate the collection of *in-situ* observations of iceberg drift, I developed the Cryologger (<https://cryologger.org/>), a low-cost, robust iceberg drift tracking beacon that can be constructed at a cost 5-10 times less than commercial alternatives. The Cryologger is based on the Arduino open-source electronics platform (<https://www.arduino.cc>), which has seen widespread adoption by scientists for numerous research applications over the past several years (e.g., Beddows & Mallon, 2018; Carlson et al., 2020; Clark et al., 2019; Planck et al., 2019; Rabault et al., 2020). The development and deployment of these novel iceberg tracking beacons began in 2018 and was intended to enhance and supplement existing iceberg observation networks within the Canadian Arctic. Observational data recorded by the tracking beacons was therefore combined with the iceberg tracks contained in the iceberg tracking beacon database, which was introduced in Section 1 and is fully detailed in Section 3.2.

3.1.1 Hardware

The design of the Cryologger takes into consideration several key principles, including cost effectiveness, power efficiency, modularity, ruggedness, and ease of use. The use of low-cost, off-the-shelf components, which are easy-to-use and do not require any specialized tools or training, makes the Cryologger accessible to researchers, citizen scientists, and hobbyists alike. Modularity and extensibility enable the beacon to be interfaced with a wide variety of easily interchangeable sensors and provides control over design complexity. This in turn allows the beacon to be customized for the specific research needs of the end-user. The selection of components that are resistant to harsh environmental conditions also ensures continuous cold weather operation.

Intended for deployments of one year or more, the Cryologger (Figure 3.1) provides long-term measurements of multiple variables, including position, recorded from its onboard global

navigation satellite system (GNSS), as well as temperature, pressure, pitch, roll, tilt-compensated heading, and battery voltage. Data are recorded hourly and transmitted over the Iridium satellite network at user-specified intervals. A summary of the components and associated costs of the Cryologger is provided in Table 3.1. A more detailed description of the design and complete bill of materials are provided on GitHub:

https://github.com/adamgarbo/Cryologger_Iceberg_Tracking_Beacon.

Table 3.1: Electronic components and associated costs for Cryologger iceberg tracking beacons (v1.0/2.0) in 2021.

Component	Description	Cost (CAD)
Rock7 RockBLOCK 9603N	Iridium satellite transceiver	\$325
Maxtena M1621HCT-P-SMA	Satellite transceiver antenna	\$60
Adafruit Pro Trinket 3V 12MHz	Microcontroller	\$25
Adafruit Ultimate GPS Breakout	GNSS receiver	\$50
Adafruit LSM303	Accelerometer/Magnetometer	\$20
Adafruit MPL3115A2	Temperature/Pressure sensor	\$15
Maxim DS3231SN	Real-time clock	\$20
Pololu 5V, 2.5A D24V22F5	Voltage regulator	\$5
Nanuk 905/903	Enclosure	\$50
Tadiran TLP-19311	Battery	\$130
Total		\$700

3.1.2 Software

The code powering the Cryologger is written in C++ and is extensible, allowing for modifications to beacon functionality to be easily made. The programming logic is intended to optimize sleep and wake cycles to reduce overall power consumption. When initially powered on, the beacon will synchronize the real-time clock (RTC) with the current date and time from the GNSS. It then sets an alarm for the first sample interval and enters a low-power, deep sleep mode. When the alarm triggers, the system wakes, records the time and acquires a GNSS position. Next, measurements of all onboard sensors are performed, including temperature, pressure and battery voltage. The orientation of the beacon (i.e., pitch, roll and heading) are measured from the onboard accelerometer and magnetometer. These data are stored into memory and if the program

determines it has reached the appropriate interval, it will attempt to transmit the data via the RockBLOCK satellite transceiver. If the data transmission fails, the message will be stored for transmission attempts at a later interval. The program then disables power to all components, sets the next alarm, and returns to deep sleep.

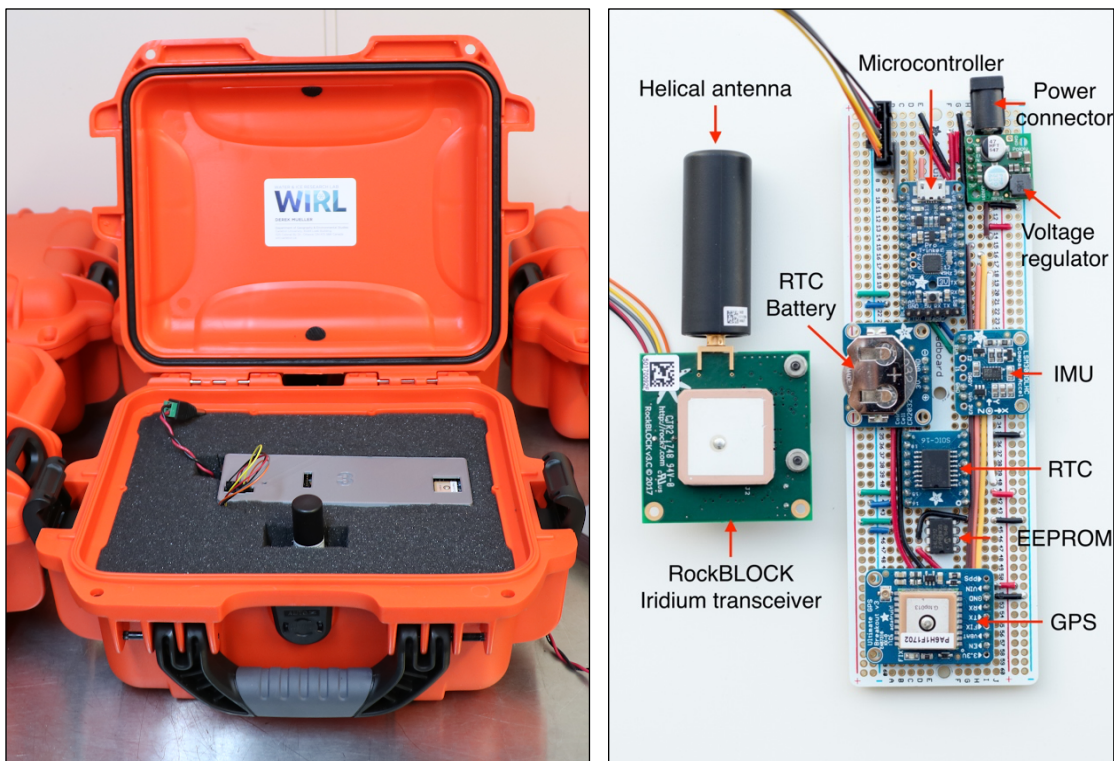


Figure 3.1: Example of an assembled Cryologger v1.0 drift tracking beacon prior to deployment in 2018 (left) and a diagram of the assembled beacon electronics (right).

3.1.3 Deployments

A total of 24 Cryologger drift tracking beacons were deployed during the 2018, 2019, and 2021 summer cruises of the CCGS Amundsen icebreaker. Deployments were made by helicopter from the CCGS Amundsen on icebergs and ice islands along the coasts of Ellesmere Island, Baffin Island and Greenland (Figure 3.2). The overall suitability of potential targets was determined by assessing the iceberg's size, shape, and location. Where possible, tracking beacons were deployed on icebergs that were large enough to potentially survive drifting south to the Grand Banks of Newfoundland and far enough away from the coast to increase the chances of being carried southward by the currents and avoid becoming grounded in shallow coastal areas. In 2019, 4 beacons were also deployed on the terminus of the Petermann Glacier in anticipation of the next

major calving event that is expected to produce an ice island approximately 185 km² in size. Details of the location of Cryologger deployments on icebergs and estimates of their physical characteristics are provided in Appendix A.

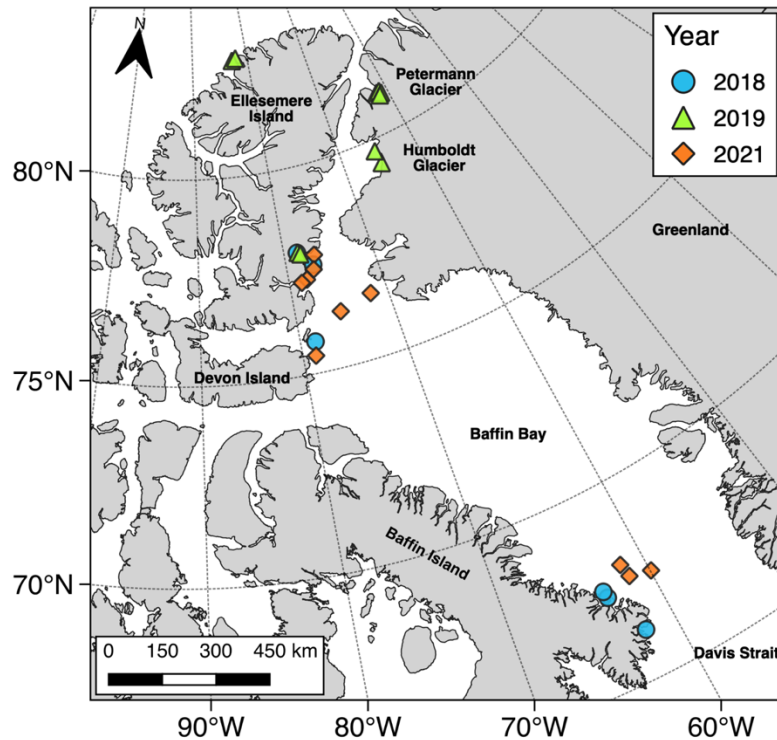


Figure 3.2: Locations of Cryologger iceberg drift tracking beacons deployed during the 2018, 2019 and 2021 field seasons.

At the time of deployment, the iceberg's shape, size, and position information was recorded. Estimates of the iceberg's waterline length were made visually and the helicopter's onboard altimeter was used to estimate the freeboard. If weather conditions permitted, a 360° aerial photo survey of the iceberg was performed to further assist in classifying the morphology of the iceberg and for later identification in satellite imagery. A compass heading measurement of the orientation of the tracking beacon was also recorded at the time of deployment, which can be used to determine the orientation of the iceberg and to track changes in its relative rotation over time. During the 2019 field campaign, an iceberg previously instrumented with a Cryologger in 2018 was revisited. After the enclosure was inspected for any signs of damage or water ingress, it was determined that the beacon was in good condition, did not require servicing, and left to continue monitoring of the iceberg.

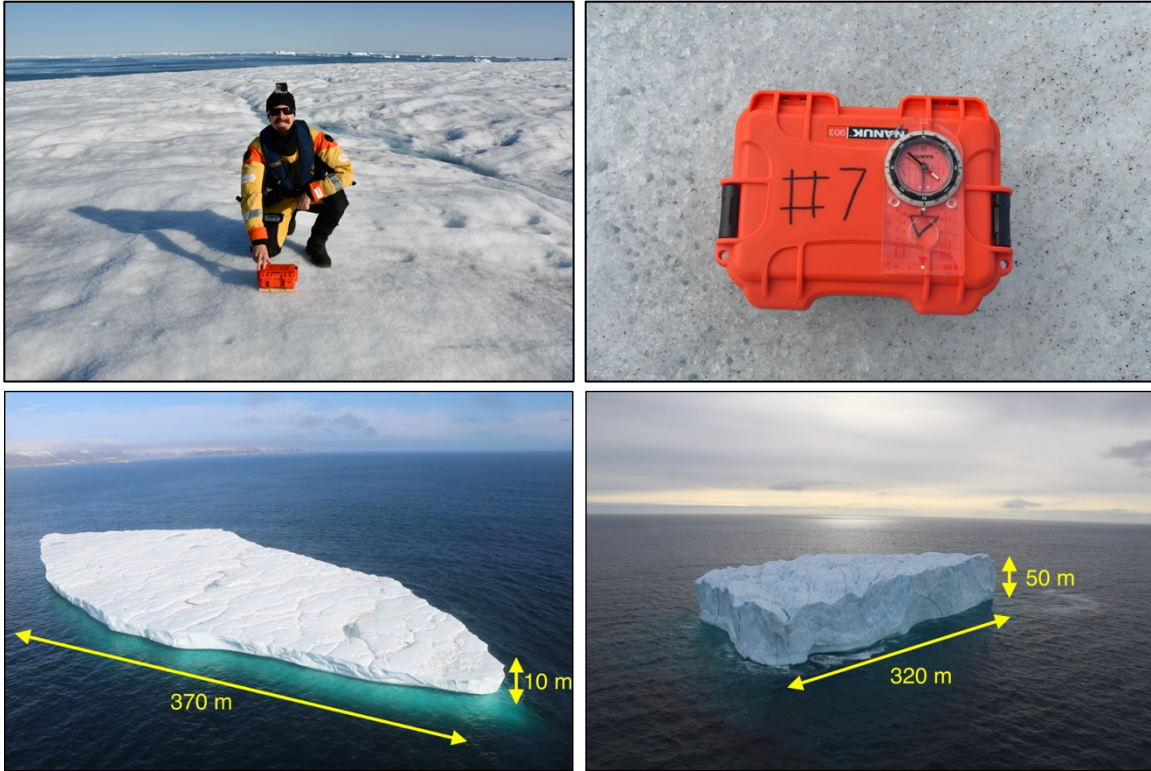


Figure 3.3: Examples of icebergs instrumented with Cryologger tracking beacons and estimated length and freeboard measurements. Deployments made on September 3, 2018, along the southern coast of Baffin Island, NU (top/left) and July 30, 2019, near Devon Island, NU (bottom right).

3.2 Iceberg tracking beacon database

Data collected from Cryologger tracking beacons were combined with the database of *in-situ* iceberg tracks compiled by Carleton University and the CIS. The database contains more than 160 unique iceberg tracks collected during the period of 1997 to 2022. Data were contributed by government, academic, and industry sources from beacons deployed on icebergs located in the western and eastern Canadian Arctic, Greenland, and off the east coast of Canada. The database includes basic classification information for some icebergs at the time of beacon deployment, including shape, size, and thickness, as well as iceberg direction, speed, and pattern data that is intended to better understand iceberg drift, and to aid in the development and validation of iceberg drift models.

3.2.1 Data selection

The iceberg tracks catalogued in the iceberg beacon database were assessed according to several criteria to determine which tracks were suitable for use in the NAIS iceberg drift model validation study. Only those tracks, or track segments, that satisfied the following conditions were retained:

1. Observations within the predefined period of study (i.e., limited to 2009-2019 due to the availability of environmental input data used to run the NAIS model).
2. Observations located within the study area (i.e., Baffin Bay to the Grand Banks of Newfoundland; see Figure 1.1).
3. The iceberg being tracked was not classified as an ice island (i.e., large tabular icebergs calved from ice shelves, due to this iceberg type being unsupported by the version of the NAIS model used in this study).
4. Observations spanned a period of at least 24 hours.
5. Observations were available at least every 3 hours.
6. The iceberg moved freely for the duration of observations (i.e., not grounded on the seafloor or encased in sea ice).

Once criteria 1-6 were applied, a total of 44 suitable iceberg tracks were identified from the iceberg beacon database (Figure 3.4). To limit the scope and scale of this study, tracks were trimmed to a maximum duration of 28 days. It was assumed that for this initial 28-day period that the dimensions of the iceberg observed at deployment remained relatively constant. Based on feedback from the CIS and IIP, the duration of hindcast model simulations to be performed in the validation study was selected to be 96 hours. The rationale being that a 96-hour period provides the opportunity to evaluate the model at various times to correspond with the needs of different users, e.g., short-term (~6-12 hours) for an iceberg management company supporting oil facilities, to long-term (3-4 days) to allow ice service agencies to establish a Limit of All Known Ice (LAKI) and notify mariners of potential ice hazards. Therefore, each of the iceberg tracks were then split into segments with a maximum duration of 96 hours, resulting in a total of 133 iceberg track segments (Figure 3.5a). For tracks not able to be evenly split into 96-hour periods, any track segments less than 24 hours in duration were discarded. Criterion 6 was then applied to each track

on a case-by-case basis, with additional cleaning of erroneous data performed manually as necessary.

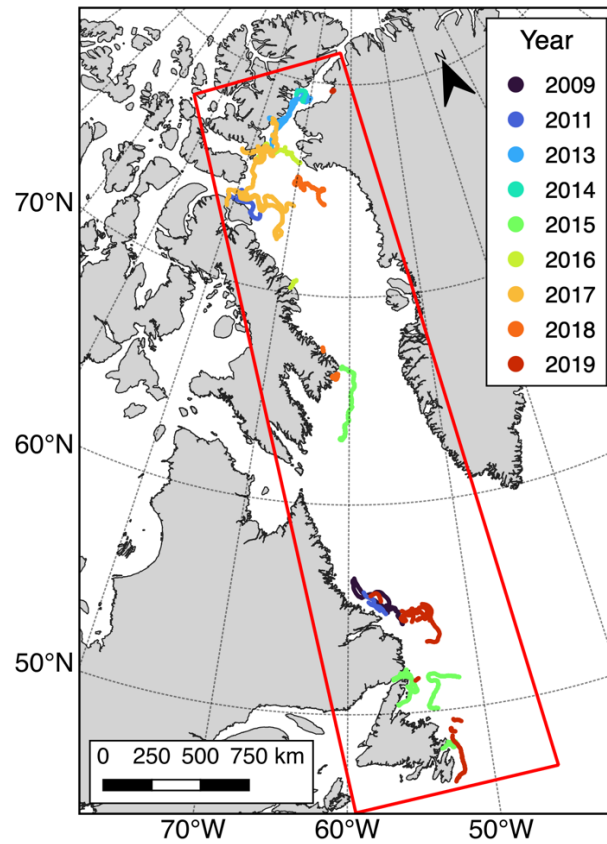


Figure 3.4: Spatial distribution of the 44 iceberg tracks extracted from the iceberg beacon database that were cleaned and trimmed to a maximum duration of 28 days. Study area outlined in red.

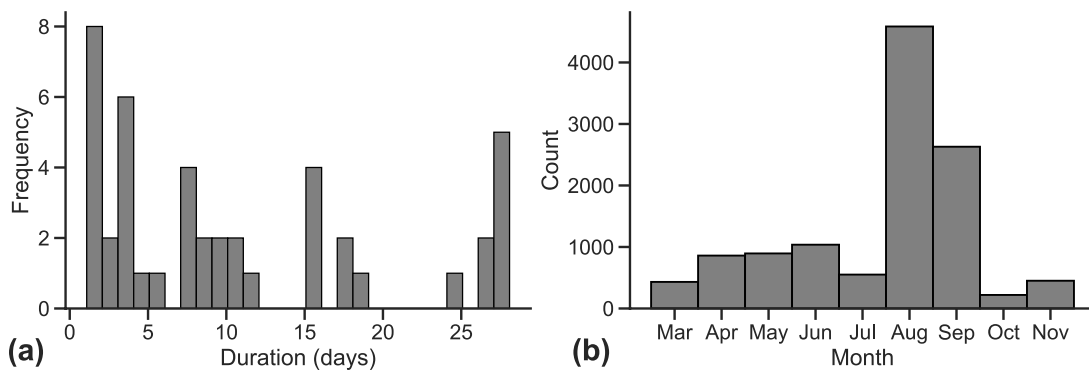


Figure 3.5: Histograms of: (a) duration of suitable iceberg tracks extracted from the iceberg beacon database, and (b) the temporal distribution of observations contained in all tracks. No tracks contained observations during the period of December to February.

3.2.2 *Data processing*

As the positional accuracy of iceberg tracking beacon data was expected to vary according to the type of beacon used to collect the data, tracks that met selection criteria 1-6 were processed using the following protocol and then reassessed to ensure that selection criteria were still met. The iceberg drift tracks were first analyzed for discontinuities in speed and location, which can be indicative of errors in the observations. This analysis also made it possible to determine if the iceberg was stationary, either due to being grounded on the seafloor, or locked in sea-ice, and additional trimming of the datasets was performed as required. To identify whether these anomalies reflected actual iceberg behaviour, plots of speed with respect to time were manually reviewed for each track. Unreasonably high average speeds ($>10 \text{ km h}^{-1}$), or large discontinuous jumps in distance were reviewed on a case-by-case basis and a decision was made if the corresponding observations should be removed from the dataset. During this step, if tracks no longer satisfied the selection criteria (i.e., they become shorter in duration than 24 hours), they were removed.

In some cases, it was necessary to determine whether beacons were situated on the icebergs for the entire duration of their track. This is because some tracking beacons can continue to transmit data once the host iceberg capsizes or fractures and transition to operation as an ocean drifter buoy. To confirm that the beacons remained on icebergs, additional criteria based on temperature measurements were imposed to eliminate transmissions made after the beacon had fallen into the ocean. When a beacon is situated on ice, the recorded temperatures typically exhibit large diurnal variations in summer and fall far below -1.8°C (the freezing point of ocean water) in the winter, with lower diurnal variability if the unit is buried by snow. However, once the beacon falls into the ocean, the reported temperatures tend to resemble the surface water temperature more closely, with relatively minor fluctuations. These temperatures can vary depending on the season and geographic location but are generally within the range of 2.5°C to 4.0°C .

For those beacons that recorded temperature, either internally (i.e., within their enclosure) or externally (i.e., sea ice/surface temperature via an external sensor), the mean and standard deviation were calculated using a 7-day moving window. The data was then visually assessed for irregular changes in temperature (Figure 3.6). In many cases, it was possible to determine when the beacon entered the ocean by observing when diurnal fluctuations in temperatures stopped, and

when the standard deviation was greatly reduced. Both factors provided a likely indicator of when the beacon was no longer located on the surface of the iceberg.

Iceberg analysis charts from the CIS (e.g., Figure 2.6) were also referenced to determine if the beacon's position was located within a grid cell that indicated the presence of an iceberg. If no icebergs were noted in the area, further investigations into whether the beacon was in fact situated in the water were performed. For example, satellite imagery was employed as an additional tool to confirm the presence/absence of an iceberg at the beacon's location. Data sources included Landsat-8, Sentinel-1 and -2, MODIS and Planet Labs (Table 3.2). If no iceberg was visible in satellite imagery acquired close in time to a reported beacon position, or if conditions were generally not favourable for the presence of icebergs (e.g., warm, open ocean), it was assumed that the beacon had transitioned to an ocean drifter buoy.

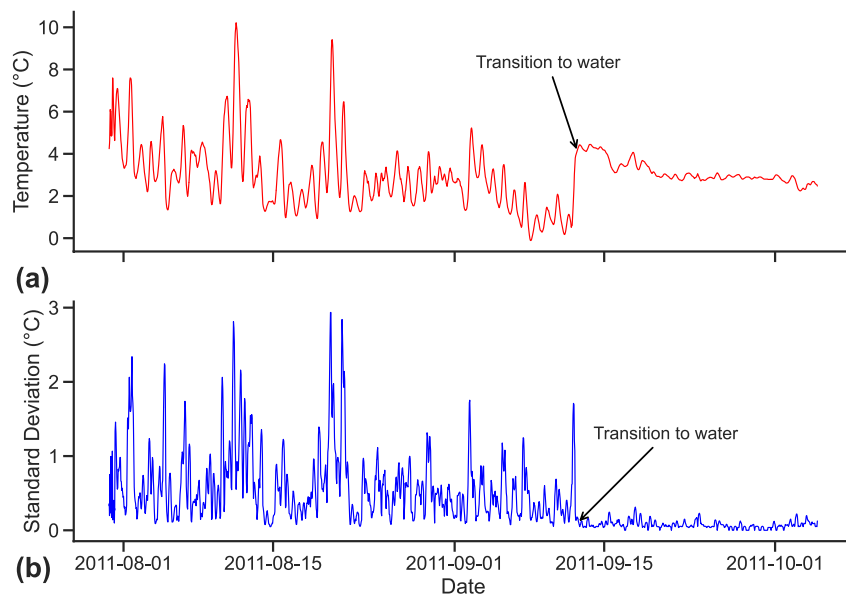


Figure 3.6: Examples of 7-day rolling: (a) mean and (b) standard deviation of iceberg beacon sea-surface temperatures (SST) used to determine the date and time at which the beacon became dislodged from the iceberg.

3.2.3 Iceberg dimensions

For icebergs contained in the iceberg beacon database with no associated shape and size information, satellite remote sensing imagery was used to estimate the morphological properties of the icebergs and general sea-ice concentration information at the time of beacon deployment. Initial deployment coordinates and date/times were used to search for available satellite scenes

from several different remote sensing data sources (Table 3.2). Once a scene was identified, the icebergs were manually delineated in QGIS (Version 3.16, QGIS 2021) to obtain length, width, and area measurements. Length was measured along the longest axis of the iceberg and width was measured at the midpoint and perpendicular to this axis.

Several challenges were encountered when attempting to identify individual icebergs within the satellite imagery, including when icebergs were situated in areas with dense iceberg concentrations, and when smaller icebergs were not clearly distinguishable due to the limitations of satellite imagery resolution. Frequent cloud cover over the study area also posed a challenge. To address these issues, satellite scenes from multiple days were downloaded and the complete beacon track was overlain atop the imagery to show the iceberg's movement over time. Using this approach, it was possible to add and/or update size and shape classification information for 32 icebergs. This data also contributed to the iceberg beacon database in the form of a new variable that includes the associated satellite scene information so that it can be easily retrieved by future users.

Table 3.2: Remote-sensing imagery and resolutions used to determine iceberg size and shape classification information.

Satellite	Imagery	Resolution (m)	Data Portal
Planet	Optical	3-5	Planet Explorer
Sentinel-1	Radar	40	Copernicus Open Access Hub
Sentinel-2	Optical	10	Copernicus Open Access Hub
Landsat-8	Optical	15	USGS EarthExplorer
MODIS	Optical	250	NASA Worldview

3.2.4 Data standardization

For some iceberg tracks in the iceberg database, observations were recorded at irregular time intervals (e.g., 5-, 10- or 30-minute intervals). In addition, over 60% of observations did not fall directly on the hour (e.g., 12:00:00). Therefore, further post-processing of the data was required to ensure measurements had regularly spaced time series. To regularize the data, linear interpolation methods were utilized in Python to standardize the data to 1-hour intervals at the start of the hour (e.g., 12:00). All related code is available on GitHub (<https://github.com/adamgarbo/Iceberg-Drift-Modelling>). This interval was selected as it is the same output format of the NAIS iceberg drift model. Having a common time series facilitates

statistical analyses of model performance. The total number of interpolations performed on the subset of the iceberg beacon database used for this study is shown in Figure 3.7. Frequently, iceberg observations only required an adjustment of a few seconds or minutes, however in some cases, interpolation resulted in the majority of observations for a given iceberg being interpolated. To ensure that no significant changes in the drift tracks of the icebergs were produced, the resulting interpolated tracks were visually compared with the raw observations (e.g., Figure 3.8). This figure provides an example of a complex iceberg trajectory to illustrate how interpolation methods could reliably standardize the time series of the tracks without the loss of small-scale drift information.

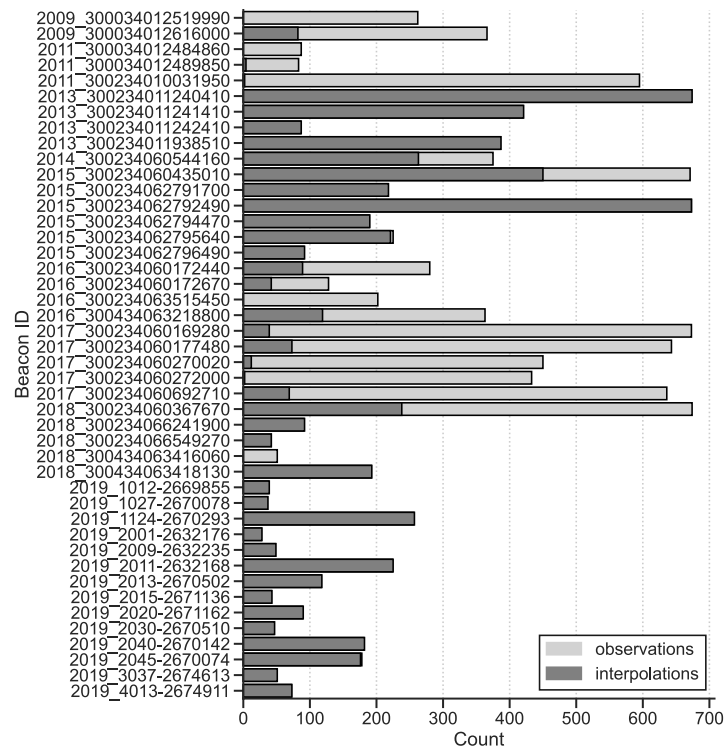


Figure 3.7: Total number of observations for each iceberg drift track and the number of interpolations required to standardize the data to a 1-hour interval.

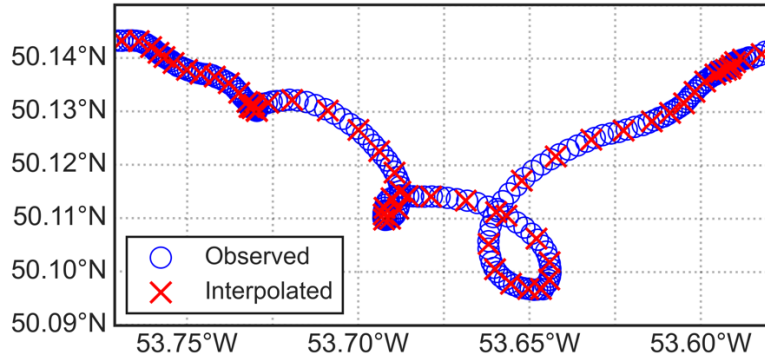


Figure 3.8: Example of an iceberg trajectory (IMEI: 300234062792490) with observations at 5-minute intervals and the resulting interpolated observations at the standardized 1-hour interval.

3.3 Environmental input data

The performance of the NAIS iceberg drift model was assessed using environmental input data from several sources, many of which required further post-processing before ingestion by the model. By default, the NAIS model is set up to run only in a forecast mode, with wind and wave conditions provided by the Canadian Meteorological Centre (CMC) forecasts, and water current conditions and sea surface temperatures provided by the Bedford Institute of Oceanography (BIO). Considerable broadening of the Python code base was required to handle additional environmental data sources, including reanalysis products, which would enable the model to be run in hindcast mode. A summary of the data sources used to drive the NAIS model simulations of iceberg drift is provided below. In addition, all related code used to make necessary modifications to the environmental input data is also available on GitHub (<https://github.com/adamgarbo/Iceberg-Drift-Modelling>).

3.3.1 Wind and wave conditions

Wind and wave forcing data required to run the NAIS iceberg model were obtained from the ERA5 climate reanalysis dataset (Table 3.3; Hersbach et al., 2020). ERA5 provides global estimates for numerous atmospheric, ocean and land variables for the period 1979 to present. The model uses a regular latitude-longitude grid that has a horizontal resolution of $1/4^\circ$ (atmosphere) to $1/2^\circ$ (ocean) and a temporal resolution of 1 hour. Data covering the period 2009-2019 were downloaded from the "Hourly data on single levels from 1979 to present" dataset on the Copernicus Climate Data Store (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>). The domain of the downloaded data was constrained to the study area (red box in

Figure 3.4). No additional data processing was required for the ERA5 data to be used with the NAIS model.

Table 3.3: Wind and wave environmental input data variables acquired from the ERA5 reanalysis at 1-hour resolution for the period January 1, 2009, to December 31, 2019.

Category	Description	Unit
Atmosphere	10 m v-component of wind	m s ⁻¹
Atmosphere	10 m u-component of wind	m s ⁻¹
Atmosphere	2 m temperature	K
Ocean	Significant height of swell waves	m
Ocean	Direction of swell waves	degrees
Ocean	Significant height of swell waves	m
Ocean	Mean period of swell waves	s
Ocean	Direction of wind waves	degrees
Ocean	Significant height of wind waves	m
Ocean	Mean period of wind waves	s

3.3.2 Ocean currents

3.3.2.1 Canadian East Coast Ocean Model

Ocean current data from the Canadian East Coast Ocean Model (CECOM; Tang et al., 2008) has traditionally been used to drive the NAIS model simulations of iceberg drift. CECOM is an ice-ocean coupled model that provides short-term forecasts of ocean current velocities, sea surface temperatures and other oceanographic variables. The CECOM domain was well-suited to this study, as it extends from northern Baffin Bay to the northern wall of the Gulf Stream and from the St. Lawrence Estuary to 42°W (Figure 3.9a). The model grid has a horizontal resolution of 0.1° x 0.1° and a vertical resolution of 10 m, with a total of 21 layers between 0 to 200 metres depth. The temporal resolution of the data is 3 hours.

CECOM is used operationally by the CIS to forecast iceberg drift and produce ice hazard products. Archived CECOM data covering the periods September 16, 2008, to July 31, 2009, and September 16, 2010, to August 31, 2020, was provided by CIS ice specialist Hai Tran through a joint project agreement with the University of Ottawa. Several post-processing steps were required to prepare the archived CECOM data for use with the NAIS model due to the data being provided

on a rotated spherical coordinate system. This involved remapping the data to a regular latitude-longitude grid with the same $0.15^\circ \times 0.1^\circ$ resolution used by the CIS and performing a bilinear interpolation to remap the data to the correct depth intervals. This post-processing ensured that the data would be readily compatible with the NAIS model and were accomplished using a Bash script and the Climate Data Operators (CDO) tool to automatically perform all necessary data extraction, remapping, interpolation, and merging steps.

3.3.2.2 Regional Ice and Ocean Prediction System

Data from the Regional Ice Observation Prediction System (RIOPS; Smith et al., 2021) was obtained to make direct comparisons against the archived CECOM data provided by the CIS. RIOPS is a new-generation ice-ocean coupled model that provides 48-hour ice and ocean forecast and analysis products. The ocean model component of RIOPS is based on Nucleus for European Modeling of the Ocean (NEMO) platform, and notably incorporates the use of tides, which have previously not been included in ocean model products used operationally by the CIS or NRC. The model domain extends from 26°N in the Atlantic Ocean, through the Arctic Ocean, to 44°N in the Pacific Ocean. The model grid has a horizontal resolution of $1/12^\circ$ (3-8 km) and a total of 75 depth layers between 0.5 m to 5902 m. The temporal resolution of the forecasts is 1 hour. RIOPS is made available as open data and can be downloaded through the Meteorological Service of Canada (MSC) Datamart (https://dd.weather.gc.ca/model_riops/).

For this study, Dr. Gregory Smith from the Meteorological Research Division at Environment and Climate Change Canada (ECCC) provided a RIOPS “nowcast” dataset covering the period January 1, 2017, to December 31, 2019. This dataset includes ocean current velocity and sea surface temperature variables and has a model domain that encompasses only the study area of interest (Figure 3.9b). Additional post-processing was required to make the RIOPS data compatible with the NAIS iceberg drift model due to the data being provided on the native NEMO tri-polar grid, which requires that the velocity vector components be rotated to a regular Cartesian coordinate system. This was accomplished by writing a custom Python script that automatically performs all necessary averaging and rotating of the ocean current vector components and by using the CDO Python library tool to interpolate, compress and output the final data products.

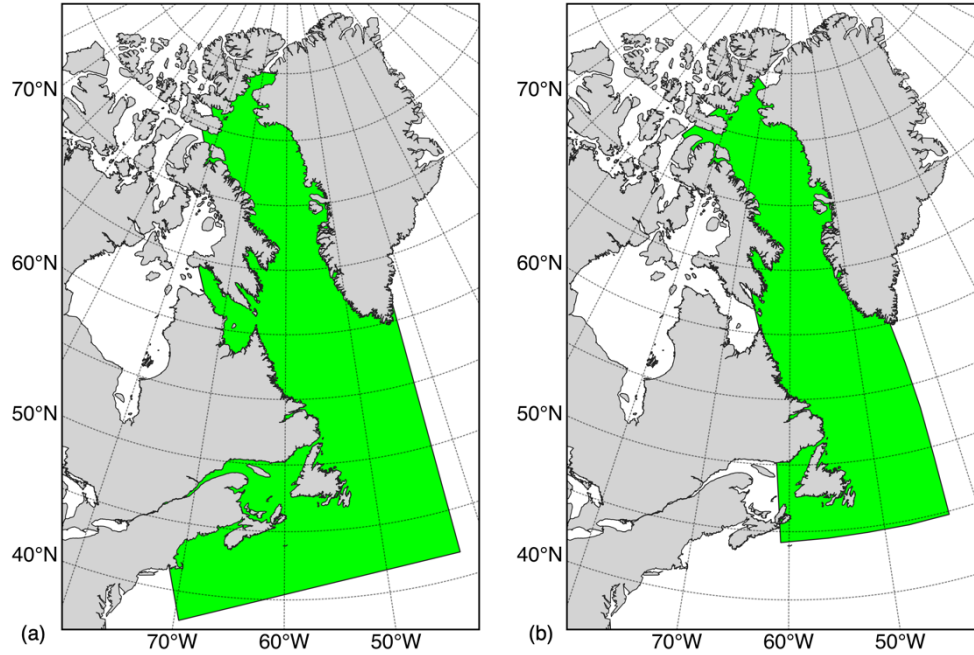


Figure 3.9: Domains of the ocean current models used in this study: (a) CECOM and (b) custom RIOPS subset.

3.3.2.3 *GLORYS12 ocean reanalysis*

To evaluate the performance of a daily mean ocean reanalysis product against the 3-hour archived CECOM and 1-hour RIOPS data, ocean current velocities and sea surface temperatures for the period January 1, 2008, to December 31, 2019, were also obtained from the GLORYS12 (hereafter, referred to as GLORYS) global ocean reanalysis (Jean-Michel et al., 2021). GLORYS provides 3D daily and monthly mean values for ocean temperature, salinity, currents, and other oceanographic variables. It is based on the NEMO ocean current model platform and driven by ECMWF ERA-Interim and ERA5 reanalyses but does not represent tidal currents due to aliasing. The model uses a regular latitude-longitude grid and has a horizontal resolution of $1/12^\circ$ and 50 layers between 0-5500 m, with vertical resolutions between 1 m in the upper 22 layers (0-100 m) to 450 m near the bottom. The domain of the GLORYS data was between 40°N to 85°N and 100°W and 40°W . Data was downloaded using the MOTU Client Command Line Interface (CLI) directly from the Copernicus Marine Environment Monitoring Service (CMEMS; <http://marine.copernicus.eu/>).

3.4 North American Ice Service iceberg drift model

All simulations of iceberg drift were made using the stand-alone Python version of the NAIS iceberg drift model developed by the NRC. The functionality of the Python code used in this study is identical to the Fortran version of the model developed by Kubat et al. (2005). Access to the NAIS model code repository was provided to the University of Ottawa through a Technology License Agreement with the NRC specifically for use in this study. Unless stated otherwise, all references to the NAIS iceberg drift model refer to the NRC Python version of the model.

3.4.1 Model operation

The NAIS iceberg model generates an hourly dynamical drift forecast from a set of initial iceberg conditions and forecast environmental variables. The initial iceberg properties required to run the model are listed in Table 3.4. With respect to shape, the model distinguishes only between tabular and non-tabular icebergs for the purposes of calculating the area and volume of the sail and keel. Where possible, iceberg length was obtained directly from the iceberg beacon database. If this information was not available, dimensions were estimated using observations of icebergs obtained from satellite imagery (Table 3.2; Section 3.2.3) If no iceberg morphology information was available, the iceberg's geometry was estimated based on an idealized shape, described further in Section 3.4.2. The NAIS model is both a drift and deterioration model, however the deterioration functionality was not enabled for this study due to the short time periods examined.

Table 3.4: Initial iceberg conditions required to run the NAIS iceberg drift model.

Variable	Description	Unit
Date	Date and time to model the iceberg drift from	UTC
Latitude	Latitude of the iceberg	decimal degrees
Longitude	Longitude of the iceberg	decimal degrees
Shape	Iceberg shape (i.e., tabular, or non-tabular)	-
Length	Mean length of the iceberg along the waterline	m
Keel Depth	Keel depth for tabular icebergs	m
Sail Height	Sail height for tabular icebergs	m

A total of thirteen environmental forcing variables were required to run the NAIS iceberg model (Table 3.5). Ocean current velocities and sea surface temperatures were acquired from the CECOM, which is used operationally by the CIS and NRC, but also from the GLORYS reanalysis and RIOPS ocean current models. Wind and wave conditions were obtained from the ERA5 climate reanalysis dataset. When performing hindcast simulations, several environmental input data sources were provided to the model at the same time, and a single model output file including all forcing data combinations was produced.

The NAIS iceberg model also relies on numerous coefficients that have been tuned to produce the best possible fit between observed and modelled iceberg drift tracks. The coefficients used in this study to perform hindcast simulations of iceberg drift are the same as the default values in current operational use by the CIS and NRC (Table 3.6) and are described in more detail by Kubat et al. (2005).

Table 3.5: List of environmental variables required to run the NAIS iceberg drift model and data sources selected for use in this study.

Category	Variable	Unit	Source
Water current	U and V of water current speed (20 levels from 0 to 190 meters depth)	m s ⁻¹	CECOM/RIOPS/ GLORYS
Water current	Water temperature	K	CECOM/RIOPS/ GLORYS
Wave	Significant height of wind waves and swell	m	ERA5
Wave	Direction of swell waves	degrees true	ERA5
Wave	Significant height of swell waves	m	ERA5
Wave	Mean period of swell waves	s	ERA5
Wave	Direction of wind waves	degrees true	ERA5
Wave	Significant height of wind waves and swell	m	ERA5
Wave	Mean period of wind waves	s	ERA5
Wind	Air temperature	K	ERA5
Wind	U and V component of wind speed	m s ⁻¹	ERA5

Table 3.6: List of coefficients used by the NAIS iceberg drift model and default values used in this study.

Input Parameter	Value	Unit
Density of ice	910	kg m ⁻³
Density of water	1030	kg m ⁻³
Density of air	1.3	kg m ⁻³
Thermal conductivity of water	0.562	W m ⁻¹ K ⁻¹
Thermal conductivity of air	0.0241	W m ⁻¹ K ⁻¹
Drag coefficient of water	1.3	-
Drag coefficient of air	1.9	-
Kinematic viscosity of water	1.79 x 10 ⁻⁶	m ² s ⁻¹
Kinematic viscosity of air	1.32 x 10 ⁻⁵	m ² s ⁻¹
Latent heat of fusion	3.33 x 10 ⁵	J kg ⁻¹
Albedo for icebergs	0.7	-

3.4.2 *Sail and keel calculations*

If an iceberg is classified as tabular, it is necessary to assign dimensions for the sail and keel geometries when initializing the drift model. The model makes estimations based on an empirical relationship with the iceberg's waterline length if the dimensions are not assigned. This relationship is based on a data fitting curve from a small number of iceberg measurements obtained from the Grand Banks of Newfoundland (Figure 3.10; H. Tran, personal communication, Jan 21, 2021). Alternatively, the model can use an empirical equation established by Barker et al. (2004) based on a simple linear relationship between keel depth and waterline length (Figure 3.10). However, due to the possibility of unrealistic estimates of keel depth being produced for icebergs with a waterline length greater than 400 m, sail and keel estimates were manually specified when running the model.

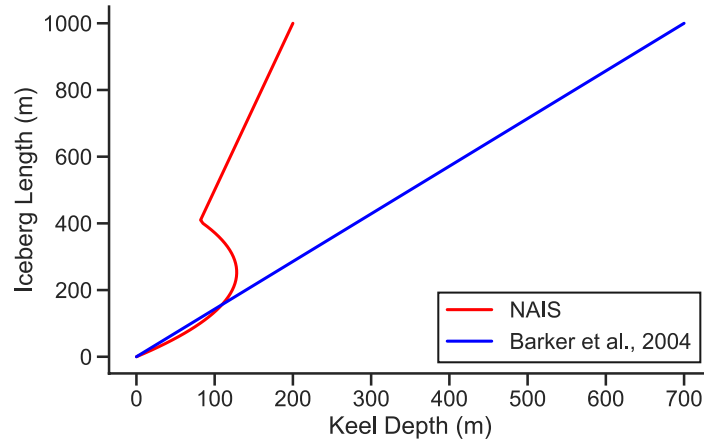


Figure 3.10: Approximations of iceberg keel based on waterline length according to NAIS method data fitting curve (red line), and idealized empirical relationship established by Barker et al. (2004) (blue line).

For the iceberg tracks used in this study, estimates of waterline length, based either on field or remote-sensing observations, were available for all 44 icebergs. However, of these, only 28 included estimates of the iceberg sail height and no icebergs included estimates of keel depth. Measurements of overall iceberg thickness, obtained from ice-penetrating radar, were available for 3 icebergs, which were partitioned into sail and keel components. For the remaining icebergs, it was necessary to estimate 16 sail heights and 42 keel depths to obtain the required inputs to execute the NAIS iceberg model.

For the 28 icebergs with an estimate of sail height, the average height to draft ratios from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (Canadian Ice Service, 2005) were used to calculate iceberg keel depth (Table 2.2). This approach was favoured over the relationship of the buoyancy of ice in sea water (e.g., 0.9), as many icebergs were irregularly shaped, which could lead to over-estimations of the iceberg's keel depth. For those icebergs with no sail or keel estimates, a value for the relationship between waterline length and keel depth of 2.19:1 was used to estimate the keel depths (Figure 3.11). This value was based on field surveys of above- and below-water portions of larger Arctic icebergs (e.g., Schild et al., 2021), which was deemed more representative of the sizes of icebergs found in Baffin Bay. The resulting relationships between iceberg length and keel depth are illustrated in Figure 3.12.

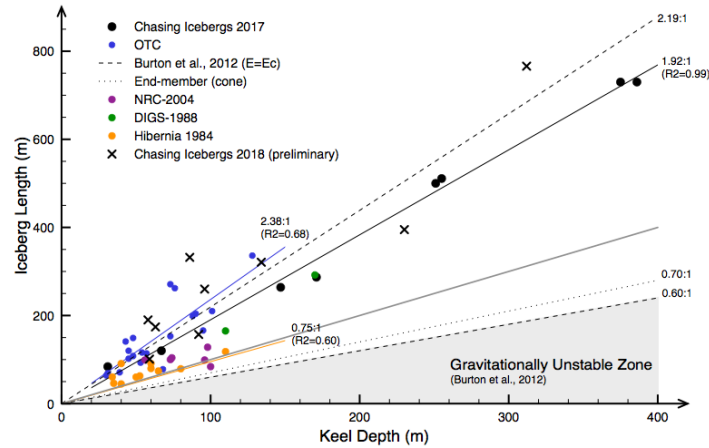


Figure 3.11: Relationships between iceberg waterline length and keel depth based on above- and below-water field surveys of icebergs in the Arctic (Schild et al., 2021).

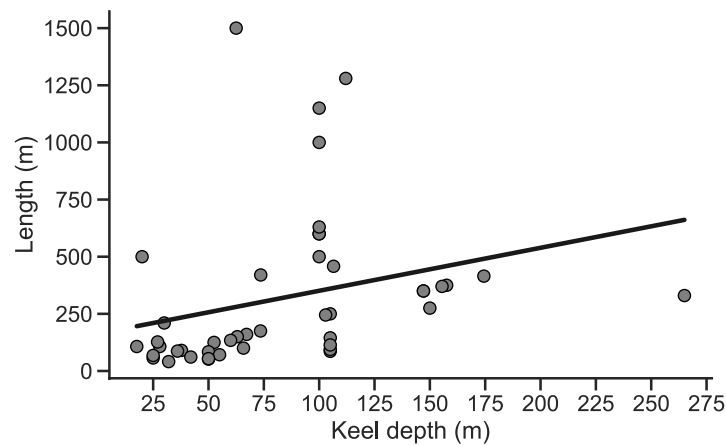


Figure 3.12: Relationships between iceberg waterline length and keel depths based on the 44 icebergs selected from the iceberg beacon database for use in this study. Regression line shown in black.

3.5 Model validation

The NAIS iceberg drift model was validated against 133 observed iceberg drift tracks from the iceberg tracking beacon database that satisfied the criteria outlined in Section 3.2. This data includes tracks collected by the Cryologger drift tracking beacons in 2018 and 2019. The NAIS model was run in hindcast mode over a 96-hour period and was initialized with observations of iceberg location, size, and shape and the default input parameters listed in Table 3.6. Hindcast simulations were run using environmental input data sources described in Section 3.3. To assess model performance, hourly modelled outputs of iceberg location throughout the 96 hours of

simulated drift were compared with the corresponding observations of iceberg locations collected with the tracking beacons.

3.5.1 *Error statistics*

In this study, several statistics were used to quantify the performance of the NAIS model's hindcast simulations of iceberg drift (Section 2.5.4). All statistical analyses were performed using Python (Version 3.9.3). As the current version of the NAIS model is not capable of interacting with the observed and modelled data files to produce the necessary output statistics, additional code was written to assess the accuracy of the modelled iceberg drift, including functions to compute the mean absolute error (MAE), root mean square error (RMSE), standard deviation (SD), coefficient of variation (CV) and other metrics detailed below. All Python code is available on GitHub (<https://github.com/adamgarbo/Iceberg-Drift-Modelling>).

Model performance was primarily assessed through the differences in distance between modelled and observed iceberg drift tracks. The distance metrics calculated for each hindcast simulation included: 1) distance error: the displacement between observed and hindcast drift tracks at a given point in time, 2) cumulative distance error: the total distance travelled by the observed and modelled iceberg tracks, 3) final distance error: the displacement between the final observed and hindcast positions, and 4) scaled distance error: the distance error divided by the length of the observed drift track. The RMSE and scaled RMSE were also calculated for all hindcast simulations at each hindcast period, as well as for each modelled iceberg track. Because the magnitudes of the errors will generally be larger for longer hindcast periods, all statistics were also aggregated by time (i.e., 24, 48, 72 and 96 hours) to examine the performance of the model at various stages of progression of the hindcast.

Differences between error metrics for different environmental forcing data at 96 hours was examined using inferential statistics. Final and cumulative distance errors were first evaluated to determine if they were normally distributed using the Shapiro-Wilk test (Harris & Jarvis, 2011). A Wilcoxon rank-sum two-tailed test evaluated the hypothesis that values in one distribution were systematically higher or lower than those in another distribution (De Veaux et al., 2018). A Kruskal-Wallis test was used to determine if at least two of the distributions systematically differed from another (De Veaux et al., 2018) and comparisons were accomplished using Dunn's post-hoc test (Dunn, 1964). Finally, the Wilcoxon signed-rank test one-tailed test evaluated whether pairs

of values were systematically higher for one of the distributions. All tests were performed using a significance level of 0.05.

3.5.2 Comparison of ocean current sources

The potential for improvement to the NAIS iceberg drift model was investigated through comparisons of model performance using ocean currents generated from three different ocean current models and reanalysis products: CECOM, GLORYS and RIOPS (Section 3.3.2). The error statistics described in Section 3.5.1 were calculated for hindcast simulations run using each of the ocean current data sources. For iceberg tracks collected between 2009 and 2019, hindcast simulations were run using ocean currents generated from the CECOM current model and GLORYS ocean reanalysis. Hindcasts were also run for iceberg tracks collected between 2017 and 2019 using the RIOPS ocean current model, which has limited data availability. At present, the CECOM ocean current model is in operational use by the CIS but will soon be replaced by the new RIOPS ocean current model. Therefore, evaluation of the effectiveness of this ocean model is of interest to the larger iceberg modelling community.

3.5.3 Spatio-temporal variability of model performance

Distance error statistics are well-suited to visualization. Two approaches were used to enable the comparison of model performance across different geographical regions. To determine if the accuracy of the modelled outputs varied by latitude, both final distance error and RMSE values calculated for each iceberg track were plotted as a function of the starting latitude of each hindcast simulation. To explore the spatial variability of the RMSE values calculated at each 1-hour timestep, a 100 km grid was laid overtop the study area and RMSE statistics were calculated for each grid cell. A limitation of this method is that it combines model outputs with different numbers of timesteps in the error calculations, which may incorrectly enlarge the error because longer forecasts will have greater uncertainties. To address this issue, only the 24-hour RMSE timestep values were used. To assess if the temporal distribution of the selected iceberg observations played a role in influencing the performance of the NAIS model, both the final distance error and cumulative distance error were grouped by season and plotted as boxplots.

3.5.4 Factors affecting model performance

Additional analysis of model performance was investigated using the iceberg waterline length variable. To determine if there was a relationship between model performance and iceberg length, both the final distance error and RMSE calculated for each iceberg track were plotted as a function of the estimated length of the iceberg used for each hindcast simulation.

3.6 Sensitivity analysis

The NAIS iceberg drift model relies on parameterizations that have been tuned to produce the best possible fit between the observed and modelled drift trajectories of icebergs along the Labrador Coast and the Grand Banks of Newfoundland. Previous studies (Allison et al., 2014; Carrieres et al., 2001; Kubat et al., 2005) have examined the sensitivity of modelled iceberg drift tracks to various input parameters (e.g., length, water and air drag coefficients) and environmental variables (e.g., ocean currents, winds, waves); however, tests relied on iceberg measurements primarily collected from the Strait of Belle Isle, the southern Labrador Shelf, and the Grand Banks region. As these results may not be representative of iceberg morphologies and environmental conditions in Baffin Bay, I performed a sensitivity analysis to explore the relative importance of model input parameters and environmental driving forces specific to this region.

The sensitivity analysis explored how output of the iceberg drift model is influenced by 12 different input parameters and environmental driving forces (Table 4.7). Iceberg and environmental input parameters were selected based on their established importance in the literature (e.g., Allison et al., 2014; Kubat et al., 2005; Turnbull et al., 2015). The validation framework assessed change to model output from perturbing each examined input parameter and environmental variable across a range of plausible values. These estimates were based on *a priori* values from the literature where possible, and in the absence of such information, informed estimates were assigned as the base value of the concerned variable. To limit the overall number of required hindcast simulations, the range of perturbations were split into 5 discrete intervals over the range of uncertainty. For example, model sensitivity to variations in iceberg length was examined by varying the observed length between 50 to 150% (i.e., base value = 400 m, intervals of 25% between 200 and 600 m).

The sensitivity analysis was conducted using observed drift tracks of 6 icebergs collected between 2017 and 2019 (Table 3.7), which ranged in duration from 50 to 96 hours. These icebergs

were selected because they included detailed size and shape information and had varying size and shape characteristics. The icebergs were spatially and temporally distributed across the area of study (i.e., Baffin Bay to the Labrador Sea), which would allow for an assessment of whether the model was better tuned in the area where it is in current operational use. Iceberg selection was also limited to 2017 onwards due to the availability of RIOPS ocean current data during this period. The RIOPS ocean current model was used as the only source of currents for hindcast simulations performed in the sensitivity analysis. As RIOPS will be replacing CECOM for use in operational iceberg drift forecasting, it was deemed that assessments of simulations produced using this source of ocean currents would yield the most value. The IMEIs of the beacons the icebergs were instrumented with are provided in Table 3.7, although in the text the icebergs are referred to by their assigned letter ID.

Table 3.7: Estimated dimensions, MANICE iceberg shape classifications, durations and locations of icebergs used in the sensitivity analysis.

ID	IMEI	Shape	Length (m)	Sail (m)	Keel (m)	Duration (hours)	Latitude	Longitude
A	300234060270020	Blocky	250	15	75	96	74.02157	-75.86064
B	300234060272000	Wedge	245	15	75	96	76.26113	-75.38774
C	300434063416060	Tabular	145	21	105	90	67.538538	-63.364703
D	300234066241900	Tabular	420	10	50	50	66.299855	-61.593859
E	1124-2670293	Tabular	134	12	60	96	48.769693	-52.550992
F	2013-2670502	Drydock	127	27	27	96	54.882727	-53.510952

Hindcast simulations were run for each observed iceberg track using the default input parameter values outlined in Table 3.6. These simulations served as the base case hindcasts. A set of four additional hindcast simulations was run for each examined input parameter as it was varied within its estimated range of uncertainty, keeping all other input parameters and variables constant. The output drift tracks were then compared to the reference cases and the model sensitivity of the concerned parameter was assessed through visual inspections of the tracks as well as quantified comparisons of model skill. The latter were based on error calculations described in Section 3.5.1. The relative importance of all parameters was then ranked according to how substantially they affected the final modelled iceberg drift positions, by calculating the mean deviation from the base case simulation position.

Chapter 4: Results

4.1 Iceberg drift tracking beacons

4.1.1 Operation

The operational lifespan of Cryologger tracking beacons deployed in 2018 and 2019 is provided in Table 4.1. Beacons deployed in 2018 achieved between 310 to 1085 continuous days of operation, with one beacon still actively transmitting as of December 2021. Beacons deployed in 2019 operated between 331 to 750 days, with five beacons actively transmitting as of December 1, 2021. The average operational lifespan of all Cryologger beacons deployed in 2018 to 2019 is 614 days. Over 80,000 recorded positions have been transmitted by the beacons deployed in 2018 and 2019 via the Iridium satellite network. Beacons deployed in 2018 achieved an average transmission duration of 11 seconds, while 2019 beacons transmitted each message for an average of 33 seconds. The most frequent cause of loss of communications with a beacon was due to snow cover or the deterioration (calving or rolling) of an iceberg and the subsequent submersion of the beacon in the ocean. In many cases, it was possible to observe major break-up events of icebergs in satellite imagery that immediately resulted in transmissions ceasing from the beacon.

The majority of beacons experienced normal operation throughout their operational lifespan. However, a small number of issues were encountered. Beacons deployed in 2018 sometimes experienced sporadic temperature and pressure measurement readings that resulted in some unusable data. The cause of this error is unknown but is suspected to be due to an intermittent sensor communication failure. Beacons deployed in 2019 experienced an issue with significant loss of communication at the beginning of winter. This was initially suspected to be due to the RockBLOCK 9603's onboard patch antenna not being able to transmit through the snow cover, which was later confirmed when the beacons began transmitting again in the spring of 2020. These beacons subsequently ceased transmitting again in the fall of 2020. An additional issue with beacons deployed in 2019 resulted from their housing in a smaller enclosure than in 2018, which was lighter and more susceptible to being blown over by strong wind gusts. Measurements from the accelerometer were used to confirm that beacons became inverted and, in this orientation, it was observed that they recorded less accurate GNSS positions. Iridium transmissions also took longer and failed more frequently when this happened.

Table 4.1: Operational lifespan, maximum speed and cumulative distance travelled for Cryologger iceberg tracking beacons deployed in 2018 and 2019, as of December 1, 2021.

Beacon IMEI #	Deployment	Days Operational	Max	Mean	Cumulative Distance Travelled (km)
	Date (yyyy-mm-dd)		Hourly Speed (km h ⁻¹)	Daily Speed (km d ⁻¹)	
300434063418130	2018-09-03	435*	4.05	3.60	1533
300434063415110	2018-08-27	310*	6.07	18.48	4348
300434063419120	2018-08-28	709*	5.68	5.04	2213
300434063411050	2018-08-28	748*	1.74	1.44	619
300434063415160	2018-09-01	1187	3.95	0.96	898
300434063416060	2018-09-01	386*	1.93	1.44	123
300434063496100**	2019-08-01	812	0.15	0.13	42
300434063392350**	2019-08-01	399*	0.24	0.16	15
300434063292950**	2019-08-01	828	0.06	0.03	7
300434063498160**	2019-08-01	837	0.09	0.07	12
300434063494100	2019-07-30	803	3.28	0.96	236
300434063392070	2019-07-30	797	2.44	1.44	379
300434063394110	2019-08-05	331*	1.12	0.72	170
300434063495310	2019-08-05	431*	6.04	18.24	2979

* Beacon was lost due to iceberg deterioration and/or rolling.

** Beacon deployed on Petermann Glacier, Greenland.

4.1.2 Iceberg drift

Beacon deployments during the 2018 field season focused on the areas of Talbot Inlet, and waters adjacent to Bylot Island and southern Baffin Island (Figure 3.2). The recorded iceberg drift tracks are shown in Figure 4.1. In terms of cumulative distance travelled, most notable was beacon 5110, which was deployed on a very large tabular iceberg near Bylot Island on August 27, 2018. After remaining grounded for several months, the iceberg became dislodged during the winter of 2019 and traveled over 4,000 km southwards before grounding and breaking up off the coast of Labrador in May 2019. Beacon 9120 was deployed on August 28, 2018 on a 5 km² ice island fragment that calved from the Petermann Glacier in 2017 and remained in the general area of northern Baffin Bay until the summer of 2020 when it became trapped in a gyre and eventually broke apart. Satellite imagery confirmed that the beacon remained on a smaller iceberg fragment that continued to drift around Jones Sound before breaking apart on the coast of Devon Island. Beacon 8130 was deployed on an iceberg near southern Baffin Island, which drifted through

several fiords before breaking apart in the winter of 2019. Beacons 6060 and 5160, which were deployed near Qikiqtarjuaq, Nunavut, were unable to escape the local shallow coastal area and frequently became grounded. Beacon 5160 eventually travelled further into a nearby fiord and washed up onshore after becoming dislodged from the iceberg as it deteriorated. This beacon transmitted without issue for over 1000 days and, as of November 2021, has continued to be used to test the durability of the electronics and capacity of the battery pack.

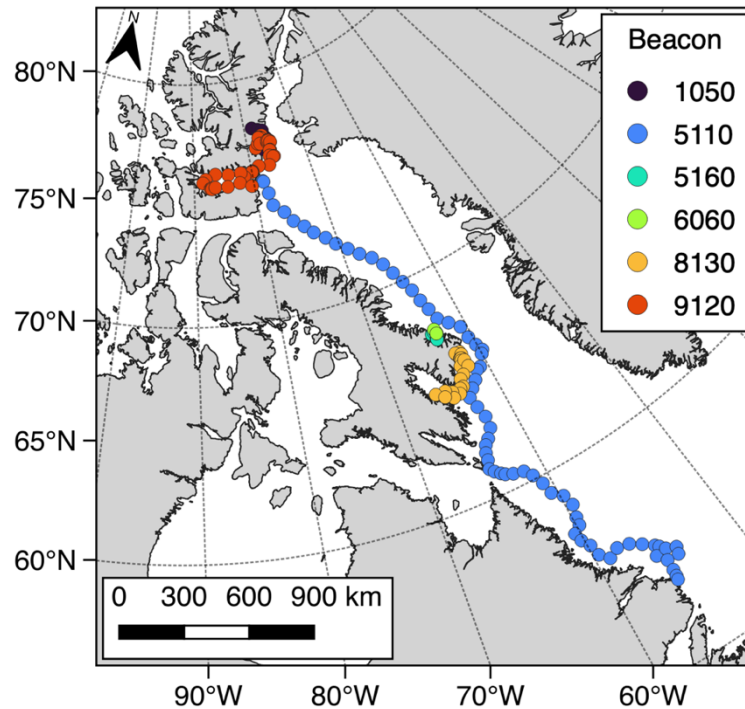


Figure 4.1: Iceberg drift tracks recorded by Cryologger beacon deployments made during the 2018 field season.

Beacon deployments in 2019 were focused on the areas of Talbot Inlet and the Humboldt and Petermann glaciers on the northwestern coast of Greenland (Figure 3.2). The iceberg tracks in Figure 4.2 reveal that many of the icebergs did not experience significant drift between the time of beacon deployment and the production of this document. Beacons 4100 and 2070, deployed on large tabular icebergs near the terminus of the Humboldt Glacier, drifted slowly in looping patterns but have remained within 100 km of their initial positions. Beacons 4110 and 5310 were deployed on icebergs near the terminus of the Trinity Glacier in Talbot Inlet. Beacon 4410 drifted slowly across Talbot Inlet until July 2020, when the iceberg catastrophically broke apart and the beacon was lost. Beacon 5310 was able to drift out of Talbot Inlet but ceased transmitting in October 2019

due to snow cover. When the beacon began transmitting again in May 2020, it had travelled over 1000 km to the southeast to southern Baffin Island. The iceberg continued to drift around the tip of Baffin Island, where it became grounded on a small island and eventually deteriorated. Of the 4 beacons deployed on Petermann Glacier, beacon 2350 ceased transmitting in September 2020. This was likely due to the beacon being blown over by a strong wind gust and eventual ingress of water into the enclosure during the following melt season. The remaining beacons deployed on the glacier continue to measure the daily displacements of the glacier (as of December 2021), in anticipation of the next major calving event. Beacon deployments in 2021 were focused on the areas of southern Baffin Island and Devon Island, and the western coast of Greenland (Figure 3.2) and initial results are currently being processed.

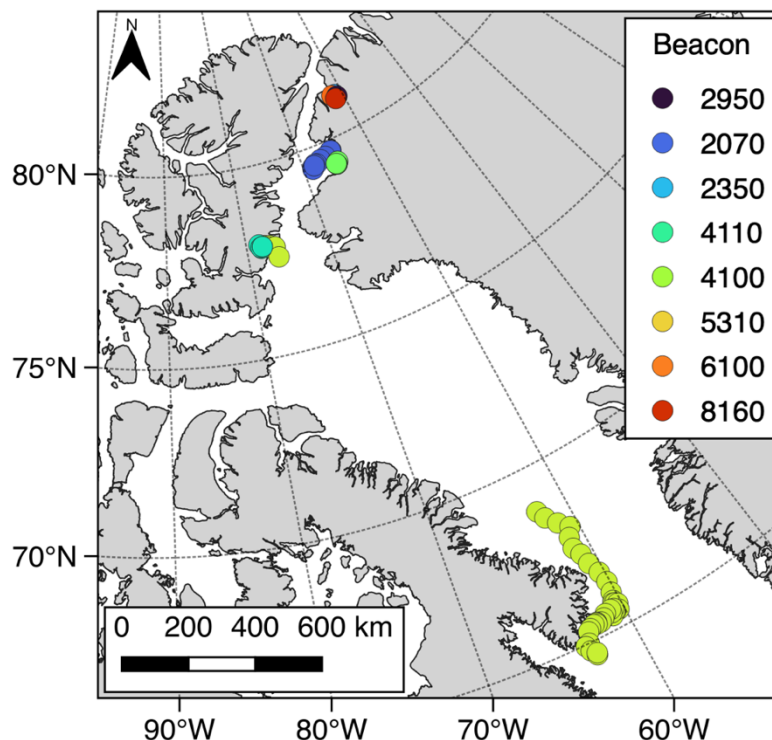


Figure 4.2: Iceberg drift tracks recorded by Cryologger beacon deployments made during the 2019 field season.

4.2 Model validation

The NAIS model was run in hindcast mode against 44 iceberg tracks selected from the iceberg beacon database that met the criteria outlined in Section 3.2.1, including tracks recorded by Cryologger tracking beacons described in Section 4.1. Each track was split into multiple

segments, each up to 96 hours in duration. The NAIS model was then run for each of the resulting 133 track segments using CECOM, GLORYS and RIOPS modelled ocean currents. Two examples of 96-hour observed and modelled iceberg tracks are shown in Figure 4.3, with Figure 4.3a showing an example of a hindcast simulation that was able to simulate the direction, distance, and general shape of the observed track very well. Figure 4.3b provides an example of when the model performed poorly and was unable to simulate the direction of the observed track, even though the cumulative distance travelled was comparable. These graphs serve to highlight that the accuracy of model outputs can vary considerably between individual hindcast simulations and sources of environmental inputs. All hindcast simulations of observed iceberg drift can be found in Appendix B.

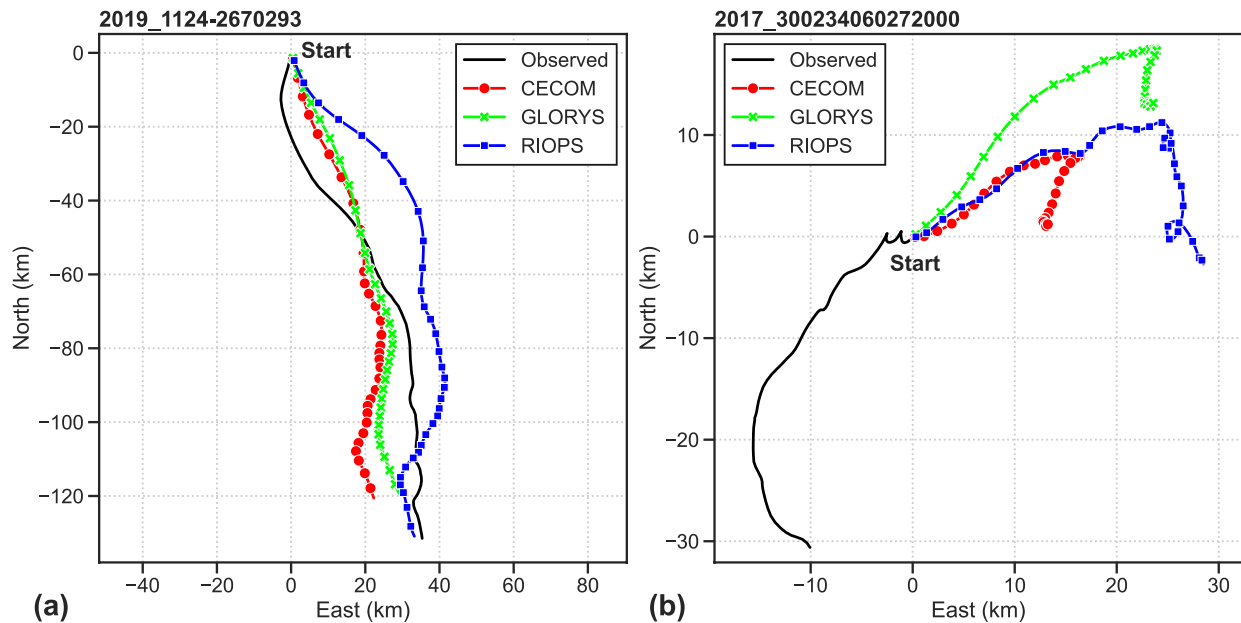


Figure 4.3: Examples of observed and modelled iceberg tracks illustrating the variability in performance of hindcast simulations of iceberg drift. Both tracks are 96 hours in duration. Markers are placed at 3-hour intervals.

4.2.1 Comparison of ocean current models

4.2.1.1 CECOM vs. GLORYS

Figure 4.4 shows the distance errors for all hindcast simulations of iceberg drift using CECOM and GLORYS modelled ocean currents for the period 2009-2019. These results illustrate that the model had considerable variability in distance error. The CECOM and GLORYS hindcasts had comparable accuracy (Table 4.2), with an overall mean distance error of 27.9 km and 24.8 km,

respectively. These errors were positively skewed, so simulations generally performed better than the mean, but both sets of hindcasts included a small number of outliers (i.e., 10-15) with very large error distances (i.e., >75 km). The mean distance error increased at a rate of approximately 11 km d⁻¹ for CECOM hindcasts and 9 km d⁻¹ for GLORYS. At each 24-hour timestep (Table 4.2), GLORYS hindcasts had slightly smaller mean distance errors. Both CECOM and GLORYS model runs had similar coefficients of variation at 24- and 48-hour timesteps, however at the 72- and 96-hour timesteps the GLORYS simulation coefficient of variation increased while the CECOM versions remained relatively constant. These results indicate that despite an overall lower mean distance error, GLORYS hindcasts have a higher standard deviation relative to the mean compared to CECOM as the hindcast duration increases.

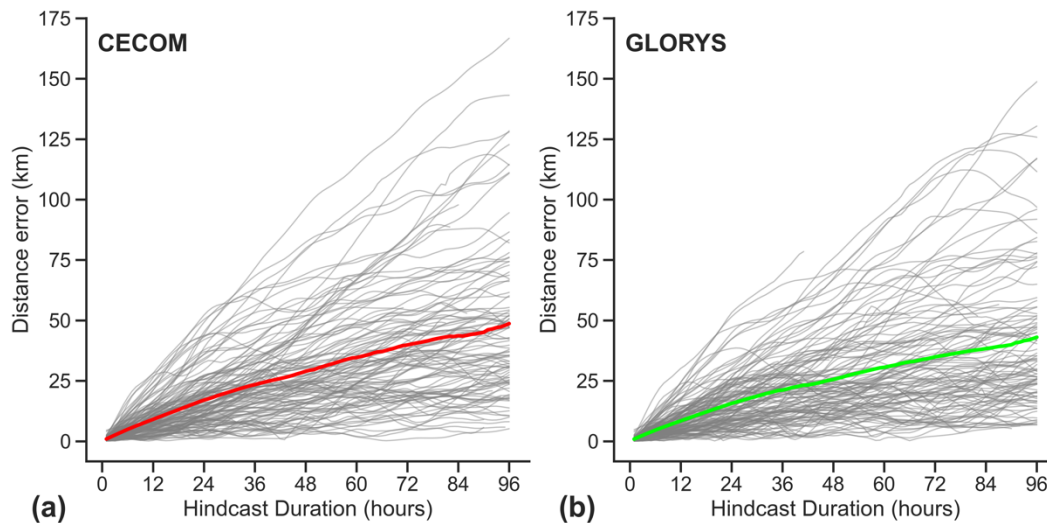


Figure 4.4: Distance error between modelled and observed positions for all 133 hindcast simulations of iceberg drift using: (a) CECOM, and (b) GLORYS modelled ocean currents for the period 2009-2019. Thin gray lines represent each hindcast simulation and the thick coloured line is the mean error distance for all model runs.

Table 4.2: Mean absolute error and coefficient of variation of hindcast simulations of iceberg drifting using CECOM and GLORYS modelled ocean currents for the period 2009-2019. Mean values calculated from all timesteps of hindcast simulations.

Duration (hours)	Mean Distance Error (km)		Coefficient of Variation (%)	
	CECOM	GLORYS	CECOM	GLORYS
24	17.01	15.66	67.96	66.70
48	28.95	25.56	64.41	64.24
72	39.83	34.91	64.66	72.73
96	48.67	43.04	66.24	71.21
Mean	27.86	24.79	66.15	68.63

The histograms in Figures 4.5a and 4.5b show the distribution of 96-hour final distance errors between observed and modelled positions for each simulation. As with mean distance error, both CECOM and GLORYS hindcasts had similar positively skewed distributions. Results of the Shapiro-Wilk tests confirm neither dataset was normally distributed ($p = <0.001$). The final distance error for CECOM hindcasts had an overall mean of 44.8 km compared to 39.5 km for GLORYS. Final distance errors for GLORYS hindcasts fell more frequently between the 0-50 km interval and less frequently between 50-100 km, compared to those of CECOM. CECOM hindcasts also produced a larger number of final distance errors greater than 100 km than the GLORYS hindcasts. These results seem to indicate that, despite similar mean errors in terms of the distance between final observed and modelled positions, GLORYS hindcasts are frequently more accurate and produce fewer extreme distance errors than CECOM hindcasts. However, based on the results of the Wilcoxon rank-sum test, the differences in 96-hour final distance error are not significant ($p = 0.11$).

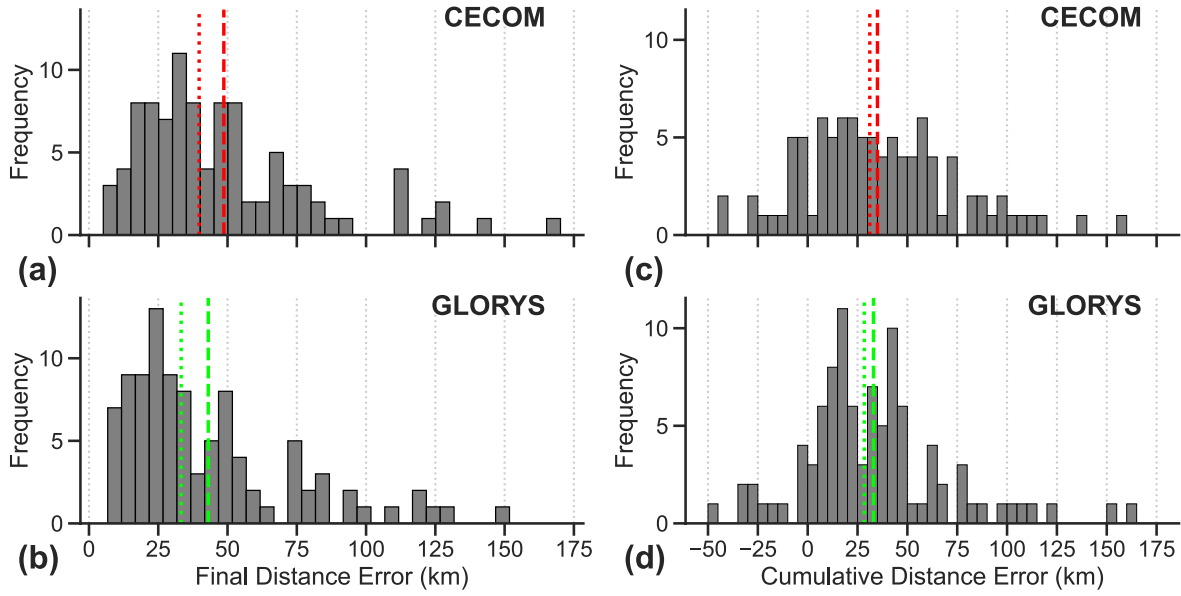


Figure 4.5: Histograms of 96-hour: (a, b) final distance error, and (c, d) cumulative distance error for 112 hindcast simulations of iceberg drift (positive values indicate overestimation of iceberg drift distance by the model, and vice versa for negative values) using CECOM and GLORYS modelled ocean currents for the period 2009-2019. Mean values denoted by dashed lines and median values denoted by dotted lines.

Figures 4.5c and 4.5d illustrate the distributions of cumulative distance errors used to determine if the model is over- or under-estimating the total distance travelled by the icebergs. To facilitate direct comparisons of hindcasts of equal duration, only 96-hour tracks were considered. The cumulative errors for CECOM hindcasts had a slightly more normal distribution compared to GLORYS, which displayed a slight bimodal distribution centered on the 25-35 km interval. However, Shapiro-Wilk tests for normality showed neither datasets were normally distributed ($p = <0.001$). Both sets of hindcasts tended to over-estimate the total drift distance, with 80% of CECOM and 83% of GLORYS estimates being greater than the observed distances. The magnitude of the over-estimations of total drift distance differed between ocean current products. GLORYS hindcasts more frequently resulted in over-estimations that fell within the 0-50 km interval, while CECOM over-estimations extended further to 75 km. Both sets of hindcasts produced a small number of cumulative distance errors between 75-165 km, but did not exhibit a clear pattern of variability between ocean current models. This is supported by the results of the Wilcoxon rank-sum test ($p = 0.55$), which indicated the 96-hour cumulative distance errors distributions did not significantly differ from one another. Of the hindcast simulations that under-

estimate the cumulative drift distance, CECOM simulations more often fell into the 0 to -15 km interval, while GLORYS hindcasts had a larger number of simulations between -25 to -35 km.

The RMSE calculated at each time step for all hindcast simulations using CECOM and GLORYS ocean current models is shown in Figure 4.6a. The number of iceberg tracks used to calculate the RMSE decreased with the hindcast period, from 133 at 24-hours to 97 at 96-hours (Table 4.3). Hindcasts using GLORYS currents performed better than CECOM currents at all timesteps. The RMSE for CECOM had an overall mean of 33.4 km compared to 30.2 km for GLORYS. The initial 24-hour hindcast period (Figure 4.6b) revealed that the RMSE for each set of hindcasts diverged after approximately 4 hours. The RMSE increased at a rate of approximately 13 km d⁻¹ and 11 km d⁻¹ for CECOM and GLORYS, respectively. The scaled RMSE, computed from the RMSE divided by the observed drift track length at each time step, was also lower for GLORYS hindcasts at all time steps, with a mean scaled RMSE of 0.84 compared to 0.97 for CECOM hindcasts. This indicates that as the cumulative iceberg drift distance increases, the model performs better using GLORYS ocean currents compared to CECOM.

Table 4.3: RMSE and scaled RMSE distance of hindcast simulations of iceberg drifting using CECOM and GLORYS ocean current models for the period 2009-2019. Count denotes number of iceberg tracks used in statistical calculations at each duration. Mean values calculated from all timesteps of hindcast simulations.

Duration (hours)	RMSE (km)		Scaled RMSE		Count
	CECOM	GLORYS	CECOM	GLORYS	
24	20.56	18.83	1.07	0.95	133
48	34.44	30.38	0.89	0.76	121
72	47.43	43.16	0.81	0.68	112
96	58.38	52.84	0.76	0.63	97
Mean	33.35	30.24	0.97	0.84	

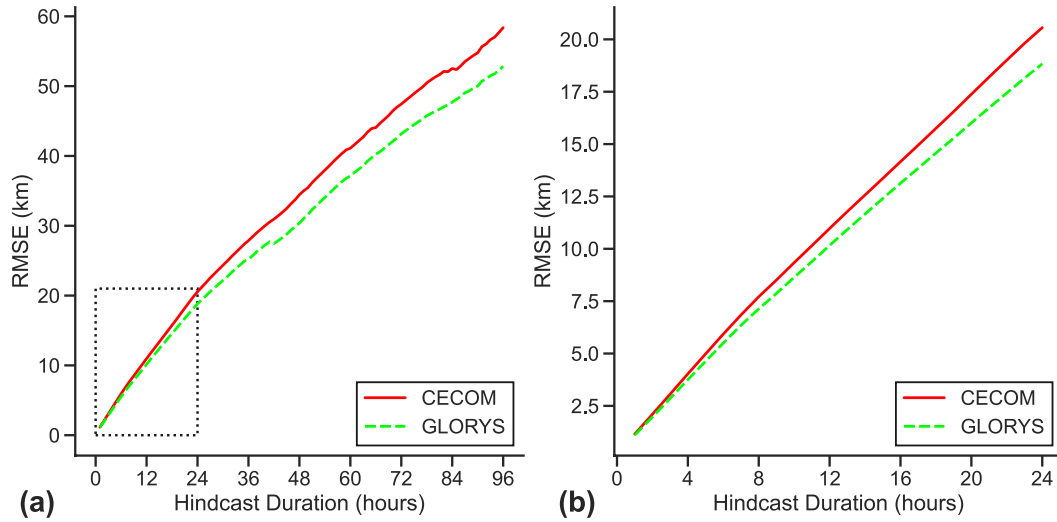


Figure 4.6: RMSE distance of hindcast simulations of iceberg drift throughout: (a) 24 hours, and (b) 96 hours, using CECOM and GLORYS modelled ocean currents for the period 2009-2019. For the 96-hour plot, there are 133, 121, 112, and 97 drift tracks that extend up to 24, 48, 72, and 96-hour hindcast durations, respectively. Dotted area in panel (a) represents zoomed area of panel (b).

4.2.1.2 CECOM vs. GLORYS vs. RIOPS

The distance errors for all hindcast simulations of iceberg drift using CECOM, GLORYS and RIOPS ocean currents for the period 2017-2019 are shown in Figure 4.7. As RIOPS data was made available starting in 2017, there are only 63 iceberg tracks available during this hindcast period, compared to 133 for the 2009-2019 period. All three sets of hindcasts displayed the same pattern of variability as the 2009-2019 simulations (Figure 4.4), with values ranging between 5-150 km. Again, a small number of distance error outliers are observed but the magnitudes are less than before. The mean distance error was comparable between hindcasts at each 24-hour timestep (Table 4.4), with overall means of 28.1 km, 26.2 km and 27.0 km for CECOM, GLORYS and RIOPS, respectively. The mean distance error increased at rate of approximately 8-12 km per day, with RIOPS hindcasts experiencing the smallest rate of change per 24-hour timestep. The coefficient of variation decreased at 48 hours for all three sets of hindcasts but increased at 72 and 96 hours. Both GLORYS and RIOPS simulations had a coefficient of variation greater at the 96-hour timestep than the initial 24-hour timestep. This indicates that the standard deviation relative to the mean is larger compared to CECOM hindcasts at time steps beyond 24 hours.

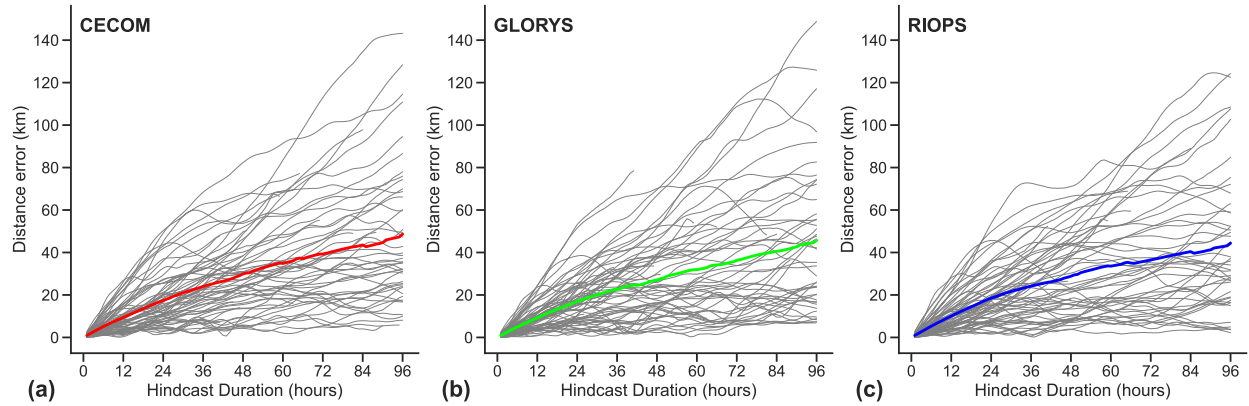


Figure 4.7: Distance error between modelled and observed positions for all 63 hindcast simulations of iceberg drift using: (a) CECOM, (b) GLORYS, and (c) RIOPS modelled ocean currents for the period 2017-2019. Thin gray lines represent each hindcast simulation and thick lines are the overall mean distance error for all model runs.

The histograms in Figures 4.8a to 4.8c show the distributions of 96-hour final distance error for all three sets of 2017-2019 hindcasts. All hindcasts had similar positively skewed distributions and an identical number of final error distance values that fell between the 0-50 km interval. The Shapiro-Wilk tests indicated none of the datasets were normally distributed ($p = <0.001$). The final distance error for CECOM hindcasts had a mean of 43.9 km compared to identical values of 40.0 km for both GLORYS and RIOPS. Notably, some hindcast simulations using RIOPS currents achieved final distance errors between 0-5 km (5%) while CECOM hindcasts were unable to produce any simulations with this level of accuracy, and GLORYS much less frequently. CECOM and GLORYS hindcasts also produced a slightly larger number of errors greater than 100 km than RIOPS hindcasts. Overall, the three sets of hindcasts were shown to produce similar results in terms of the distance between final observed and modelled positions. This is confirmed by the result of the Kruskal-Wallis test ($p = 0.71$), which showed there is no statistically significant difference between the three distributions.

Table 4.4: Mean absolute error and coefficient of variation of hindcast simulations of iceberg drifting using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. Mean values calculated from all timesteps of hindcast simulations.

Duration (hours)	Mean Distance Error (km)			Coefficient of Variation (%)		
	CECOM	GLORYS	RIOPS	CECOM	GLORYS	RIOPS
24	17.44	16.92	18.50	70.83	66.75	66.13
48	29.92	27.07	28.82	59.67	64.39	65.01
72	39.27	36.27	36.52	64.56	77.4	71.08
96	48.66	45.72	44.38	67.41	74.65	73.08
Mean	28.10	26.20	27.00	65.78	69.62	68.43

Figures 4.8d to 4.8f illustrates the distributions of 96-hour cumulative distance errors for all hindcast simulations. All three sets of hindcasts had slightly bimodal distributions, with CECOM and GLORYS centered around the 25-35 km interval and RIOPS around 15-20 km. Shapiro-Wilk tests confirmed no datasets had a normal distribution ($p = <0.001$). Cumulative drift distance was over-estimated by 81% of CECOM and GLORYS hindcasts, compared to 70% of RIOPS simulations. The magnitude of the over-estimations of total drift distance varied between ocean current products. CECOM and GLORYS hindcasts more frequently resulted in over-estimates that fell within the 0-50 km interval compared to RIOPS. All sets of hindcasts also produced an equal number of cumulative distance errors over 75 km, although CECOM and GLORYS extended further out to 115 km. RIOPS produced the greatest number of hindcasts that under-estimated the cumulative drift distance, with simulations most often falling into the 0 to -10 km interval, but also extending further to -40 km. The results of Kruskal-Wallis test ($p = 0.01$) indicated at least two of the datasets significantly differed from each other. A subsequent Dunn's post-hoc comparison test confirmed that a significant difference existed between both CECOM and RIOPS ($p = 0.006$) and GLORYS and RIOPS ($p = 0.015$) datasets however, there was no significant difference between CECOM and GLORYS error.

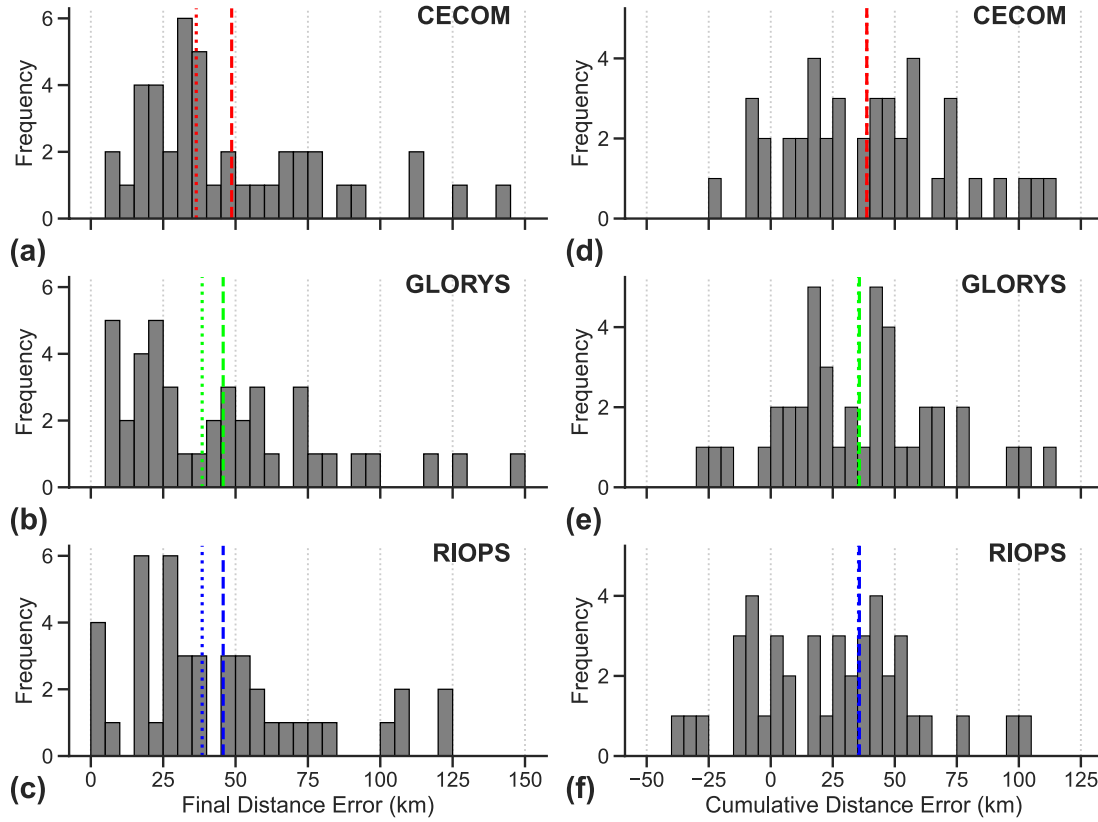


Figure 4.8: Histograms of 96-hour: (a, b, c) final distance error and (d, e, f) cumulative distance error for hindcast simulations of iceberg drift (positive values indicate overestimation of iceberg drift distance by the model, and vice versa for negative values) using CECOM, GLORYS, and RIOPS modelled ocean currents for the period 2017-2019. Mean values denoted by dashed line and median values denoted by dotted lines.

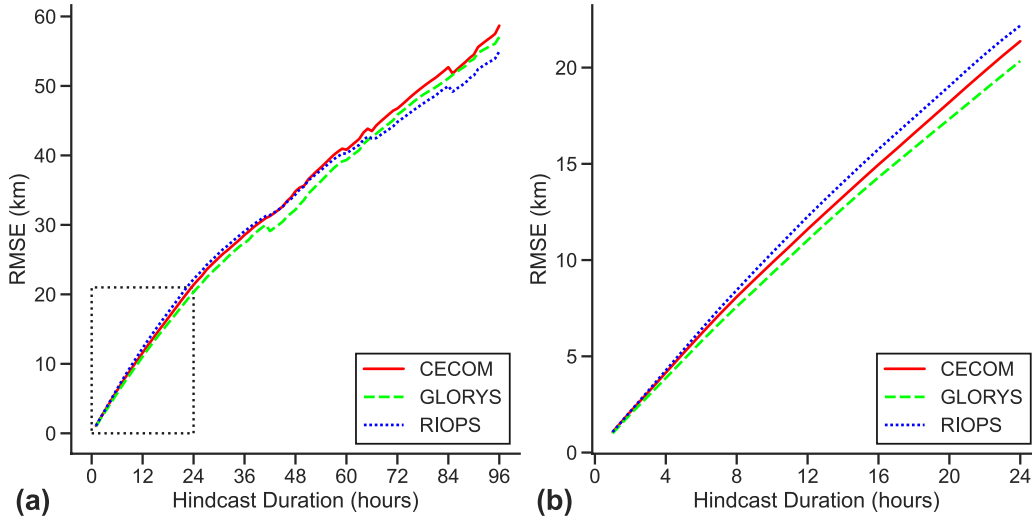


Figure 4.9: RMSE distance of hindcast simulations of iceberg drift at: (a) 96 hours, and (b) 24 hours using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. In plot (b) there are 63, 55, 47, and 42 drift tracks that extend up to 24, 48, 72, and 96-hour hindcast durations, respectively. Dotted area in panel (a) represents 24-hour zoomed area in panel (b).

The RMSE calculated at each hourly time step for all three sets of hindcasts is shown in Figure 4.9. RMSE values closely covaried throughout the 96-hour hindcast period. Sharp drops in RMSE most likely corresponded to the number of available iceberg tracks, which decreased from 63 to 42 at 24- and 96-hour timesteps, respectively (Table 4.5). GLORYS hindcasts were shown to perform slightly better than both CECOM and RIOPS during the first 72 hours of the hindcast period and RIOPS had slightly lower RMSE than the other two products beyond 72 hours. The initial 24-hours of the hindcast period (Figure 4.9) clearly showed that RIOPS hindcasts performed worse than both CECOM and GLORYS. The RMSE was again shown to diverge after approximately 4-8 hours. The RMSE increased at a rate of approximately 12 km d^{-1} for CECOM and GLORYS hindcasts and 10 km d^{-1} for RIOPS. The scaled RMSE values had a mean of 0.87, 0.85 and 0.99 for CECOM, GLORYS and RIOPS hindcasts, respectively, and was highest for RIOPS at all time steps. This indicates that as the cumulative drift distance increases, the model performed the worst using RIOPS ocean currents.

Table 4.5: RMSE and scaled RMSE of hindcast simulations of iceberg drifting using CECOM, GLORYS and RIOPS modelled ocean currents for the period 2017-2019. Count denotes number of iceberg tracks used in statistical calculations at each duration. Mean values calculated from all timesteps of hindcast simulations.

Duration (hours)	RMSE (km)			Scaled RMSE			Count
	CECOM	GLORYS	RIOPS	CECOM	GLORYS	RIOPS	
24	21.37	20.34	22.18	0.98	0.92	1.20	63
48	34.84	32.19	34.38	0.82	0.77	0.95	55
72	46.75	45.86	44.81	0.73	0.71	0.81	47
96	58.68	57.06	54.97	0.63	0.66	0.69	42
Mean	33.54	32.37	32.84	0.87	0.85	0.99	

4.2.2 Temporal variability of model performance

To explore if the performance of the NAIS model was influenced by seasonality, final and cumulative distance errors were aggregated by season (Figure 4.10). The number of available iceberg tracks for each season is listed in Table 4.6. Observed iceberg tracks of all durations (i.e., 24-96 hours) were used in this analysis. It is of note that there were a smaller number of tracks available in the spring, and no tracks available in the winter. This is due to the fact that iceberg tracking beacons are most commonly deployed in the Arctic during the summer field season, when sea ice-free conditions allow ships to access iceberg-infested waters. Model performance for the 2009-2019 hindcast period, in terms of the final distance error, did not exhibit any noticeable patterns of variability between seasons or ocean current models (Fig. 4.10a). However, model runs with GLORYS currents performed slightly better than CECOM in summer and fall and were comparable in the spring. For the 2017-2019 hindcasts which include RIOPS currents, a more noticeable difference in model performance between seasons can be observed (Figure 4.10c). Final distance errors in the spring were significantly less than in the summer and fall seasons, which is likely explained by the limited number of data points during the spring period (i.e., 6). The largest range of final distance error values observed are in the summer, with GLORYS performing slightly better than CECOM and RIOPS. Model performance in the fall was considerably better than in the summer, with both CECOM and GLORYS hindcasts performing slightly better than RIOPS.

The cumulative distance error grouped by season is shown in Figures 4.10b and 4.10d for 2009-2019 and 2017-2019, respectively, which are used to determine if a model tends to over- or under-estimate the total distance travelled by the iceberg during a specific time of year. During the 2009-2019 hindcast period, simulations more frequently under-estimated the total iceberg drift

distance and had lower cumulative errors during the spring than in summer and fall. While both summer and fall seasons are similar in their over-estimates of total distance, GLORYS hindcasts are shown to have slightly lower cumulative distance error, and less variability. For the 2017-2019 hindcast period, values of cumulative distance error in the spring are closer to zero and have less variability, which again is likely due to the limited availability of data during this season. During both the summer and fall seasons, hindcast simulations tended to over-estimate the total drift distance. RIOPS simulations consistently had values closer to zero, meaning that there is neither a tendency to over- nor under-estimate drift, and that the model performance was improved using this ocean current model. Notably, during the fall the variability of GLORYS was considerably smaller than CECOM and RIOPS.

Table 4.6: Number of iceberg tracks included in each season for the 2009-2019 and 2017-2019 hindcast periods.

Hindcast Period	Spring (Mar-May)	Summer (Jun-Aug)	Fall (Sept-Nov)	Winter (Dec-Feb)
2009-2019	25	68	40	0
2017-2019	6	39	18	0

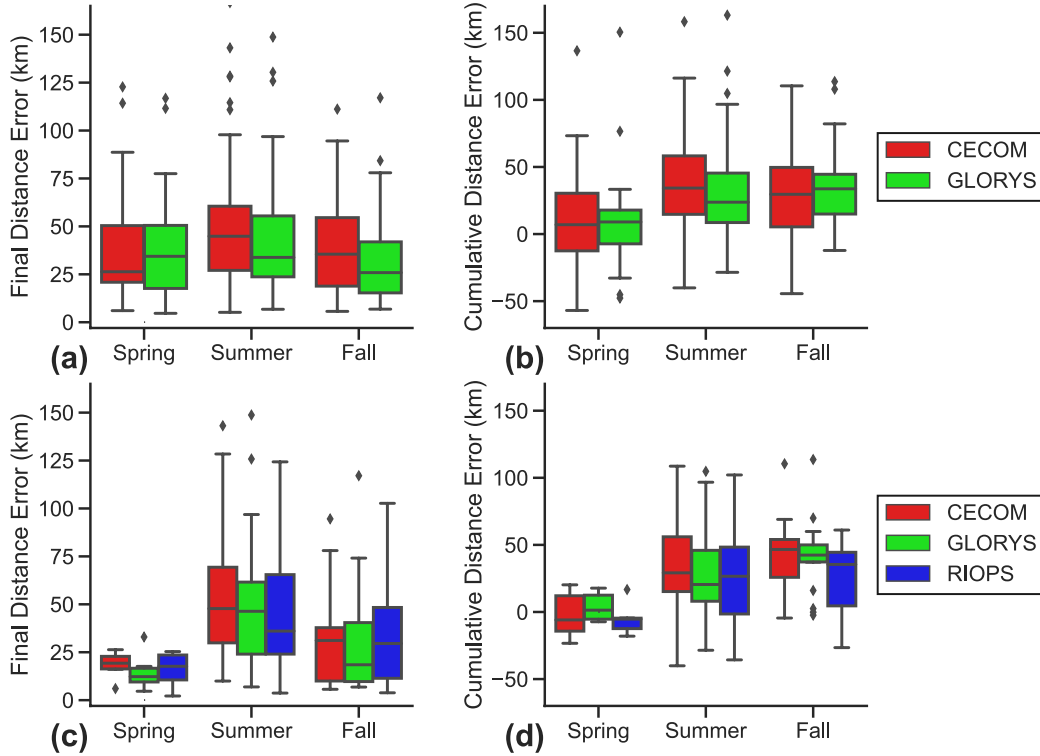


Figure 4.10: Boxplots of: (a, c) final distance error, and (b, d) cumulative distance error as a function of season for all hindcast simulations of iceberg drift using: (a, b) CECOM and GLORYS modelled ocean currents for: (a, b) 2009-2019, and (c, d) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Boxplots illustrate inter-quartile range of 25th to 75th percentiles. Outliers denoted by diamonds.

4.2.3 Factors influencing model performance

Figure 4.11 illustrates the relationship between iceberg waterline length and the cumulative distance travelled by icebergs after 96 hours of observed drift (iceberg tracks shorter than 96 hours were not included in this analysis to remove the influence of model duration). The results in Figure 4.11 show that there was a slight trend of decreasing cumulative distance with increasing iceberg length. Those icebergs with lengths less than 500 m exhibited the greatest amount of variability, with cumulative distances ranging between 25-200 km. While there are a fewer number of available icebergs with lengths greater than 1000 m, the total distances travelled showed less variability, with icebergs tending to drift between 50-125 km. Based on the iceberg tracks used in this study, smaller icebergs have the potential to drift further, leading to potentially greater distance error magnitudes.

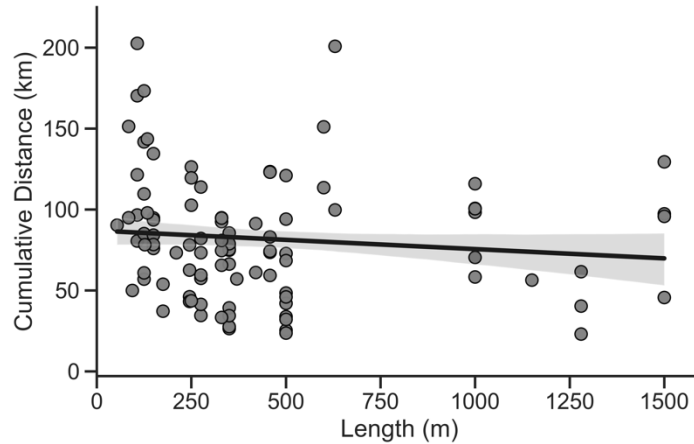


Figure 4.11: Cumulative distance of observed iceberg tracks at 96-hours as a function of iceberg waterline length. Regression line and shaded 95% confidence interval are shown.

The results of Figure 4.12 illustrate the RMSE calculated for entire iceberg tracks as a function of iceberg length. Iceberg tracks of all durations (i.e., 24-96 hours) were used in this analysis. It is notable most icebergs used in the validation study had a length of less than 500 m and a small number of icebergs with lengths between 1000 and 1500 m were included in the 2009-2019 hindcast period. For both the 2009-2019 and 2017-2019 hindcast periods, there was a general trend of decreasing RMSE with increasing iceberg length for all CECOM, GLORYS and RIOPS hindcasts. For the 2009-2019 hindcasts, there was considerable variability in RMSE for icebergs between 100 and 600 m length, with RMSE values ranging between 5-80 km (Figure 4.12a). However, it is observed that model performance generally improved as the iceberg length increased. There were also considerably fewer larger icebergs with extremely high RMSE values. As expected, RMSE values for icebergs with lengths greater than 1000 m were lower overall and ranged between 5-35 km. Model performance for the 2017-2019 hindcasts was comparable to 2009-2019, although RMSE values had less variability and there were generally lower values across the range of iceberg lengths for 2017-2019 (Figure 4.12b).

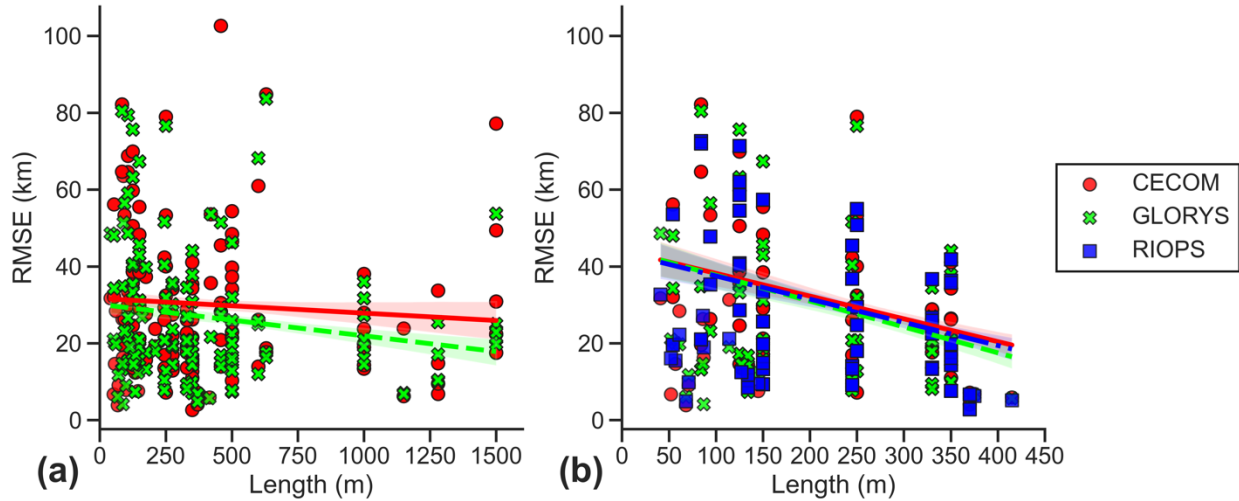


Figure 4.12: RMSE as a function of iceberg waterline length for all hindcast simulations of iceberg drift using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.

4.2.4 Spatio-temporal variability of model performance

Figure 4.13 shows the RMSE calculated for each iceberg track as a function of the starting latitude for both the 2009-2019 and 2017-2019 hindcast periods. Iceberg tracks of all durations (i.e., 24-96 hours) were used in this analysis. The gaps in the data around 60°N corresponded to a lack of beacon deployments and associated observations in the iceberg beacon database during the first 28-days of observed iceberg drift. When considering model performance, both hindcast periods displayed a slight trend of decreasing performance with increasing latitude between 45°N and 55°N and increasing model performance with increasing latitude between 72°N and 80°N (Figure 4.13). The distribution of RMSE values between 45°N and 55°N for both hindcast periods was shown to have two distinct groupings: the majority of values fell between 5-50 km, with a slightly smaller group between 50-80 km. Between 72°N and 80°N the distribution of errors generally extended from 5-60 km, with smaller number of errors extending to 80 km. Model performance was best between 62°N and 70°N, where the RMSE had considerably less variability and ranged between approximately 5-50 km. For the 2017-2019 hindcasts, the distribution of RMSE around 55°N was comparable to that of 72°N and 80°N (Figure 4.13b). Hindcasts between 45°N and 53°N were observed to perform better than at most latitudes, apart from the small number of simulations around 65°N. Regression lines showed the same pattern of increasing RMSE with latitude for the CECOM ocean model and decreasing RMSE with the GLORYS ocean model

(Figure 4.13a). During the 2017-2019 hindcast period, the regression lines (Figure 4.13b) showed the RMSE to increase with latitude for the CECOM, GLORYS and RIOPS ocean models, however more closely than the 2009-2019 period.

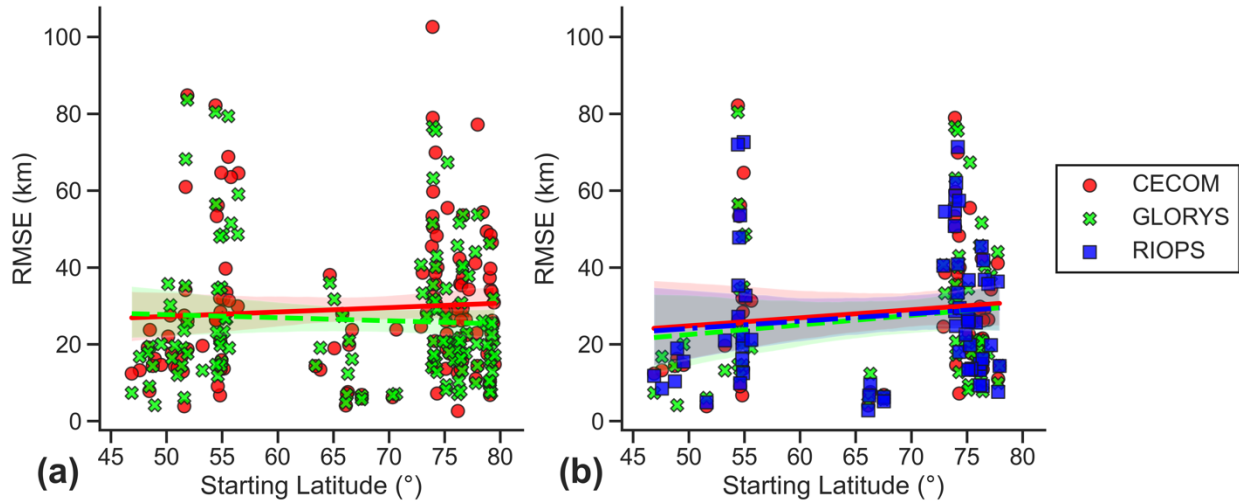


Figure 4.13: RMSE as a function of the starting latitude of observed iceberg drift tracks for hindcast simulations using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.

Figure 4.14 compares model performance for 24-hour tracks in terms of RMSE for the hindcast period 2009-2019 across two different geographical regions: north of 65°N and south of 60°N. No hindcast simulations of observed iceberg drift were available between 60°N and 65°N. It should be noted that due to the limited number of available iceberg tracks in each 100 km grid cell, results are in many cases representative of only a single iceberg track. When comparing the performance of the model north of 65°N, both GLORYS and CECOM modelled ocean currents were comparable in many regions, including the southern tip of Baffin Island, northern Baffin Bay and Nares Strait. In these regions, 24-hour RMSE values were generally below 25 km. However, both ocean models performed poorly north of Bylot Island, where RMSE values increased to 35-45 km for CECOM and 25-35 km for GLORYS ocean models. South of 60°N there were noticeably fewer grid cells, however model performance was comparable to north of 65°N. In this region, model runs with the CECOM ocean currents general outperformed those with GLORYS currents, especially on the northern coast of Labrador, where 24-hour RMSE values

increased to 35-45 km for the GLORYS modelled currents and 30-35 km for CECOM modelled currents.

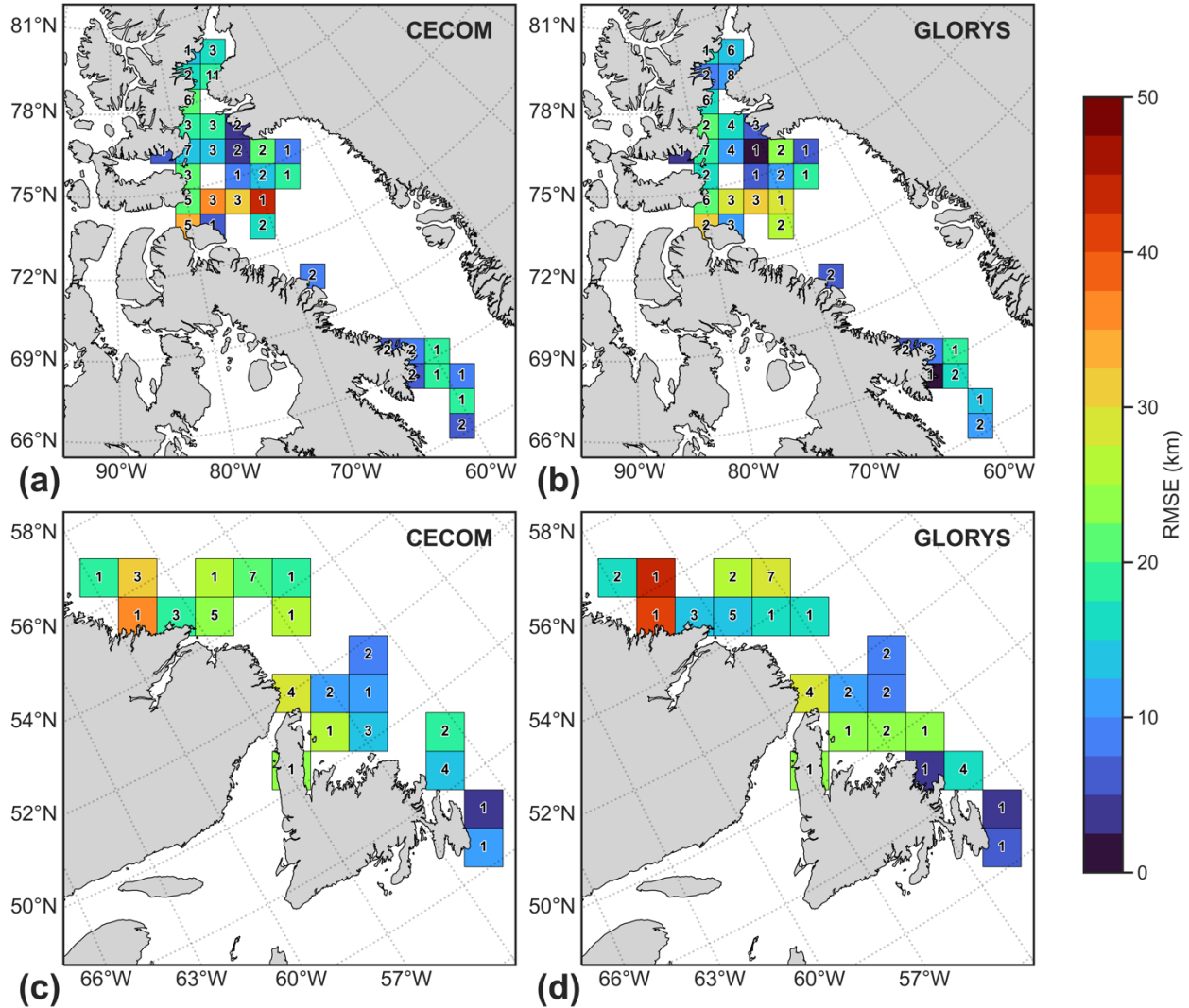


Figure 4.14: RMSE distance for 24-hour hindcast simulations of iceberg drift: (a, b) north of 65°N; (c, d) south of 60°N using: (a, c) CECOM and (b, d) GLORYS modelled ocean currents for the period 2009-2019.

Figure 4.15 illustrates 24-hour RMSE model performance for the hindcast period 2017-2019 across the regions north of 65°N and south of 60°N. No hindcast simulations of observed iceberg drift were available between 60°N and 65°N or 67.5°N and 72.5°N. Due to the scarcity of data for this period, each 100 km grid cell may only include a single iceberg track. When comparing the performance of the model north of 65°N, comparable results across all areas were

observed for CECOM, GLORYS and RIOPS modelled ocean currents. The 24-hour RMSE values were generally below 25 km. Again, all ocean models performed least well in the area north of Bylot Island, with RIOPS performing the worst, followed by CECOM and GLORYS. As in Figure 4.14, model performance was generally comparable between all ocean current models, with RMSE values ranging between 5-30 km. The iceberg model performed better off the coast of Newfoundland and slightly worse off the coast of Labrador. Overall, there was no clear pattern in the quality of iceberg forecasts between modelled ocean currents, although CECOM and GLORYS generally outperformed RIOPS off the coast of Newfoundland and Labrador.

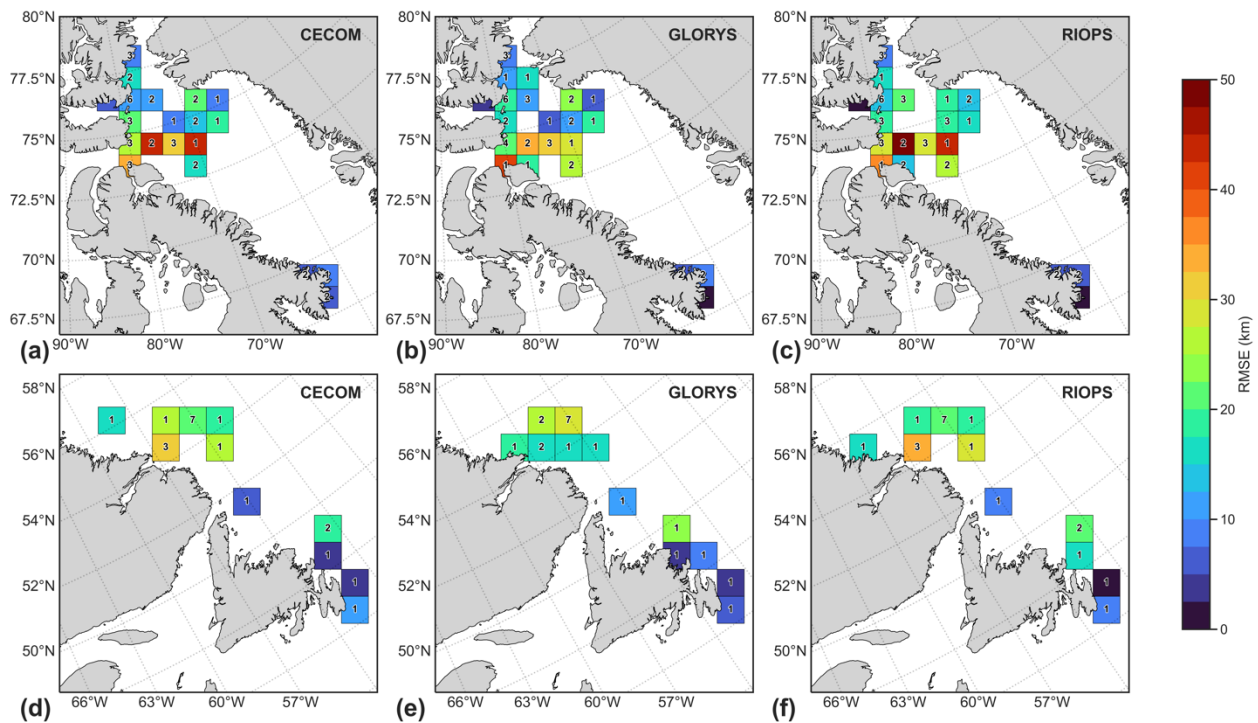


Figure 4.15: RMSE distance for 24-hour hindcast simulations of iceberg drift north of 65°N (top) and south of 60°N (bottom), using: (a, d) CECOM, (b, e) GLORYS, and (c, f) RIOPS modelled ocean currents for the period 2017-2019.

4.3 Sensitivity analysis

A sensitivity analysis was performed to explore the relative importance of various model input parameters and environmental driving forces, and to evaluate whether the current configuration of the NAIS iceberg model is suitable for iceberg morphologies and environmental conditions specific to Arctic regions. Model sensitivity to changes in model input parameters and environmental driving forces (Table 4.7) were examined using hindcast simulations of 6 icebergs (Table 3.8) at hourly intervals up to a period of 96 hours. All hindcasts were run using

environmental input data from RIOPS modelled ocean currents and winds and waves from the ERA5 reanalysis (Section 3.6). As many of the resulting iceberg drift tracks were too close to distinguish from each other, not all visualizations of tracks are included in this section.

The summary results from the sensitivity analysis are provided in Table 4.7. The mean deviation, the mean distance in kilometers between the base case hindcast position and the modelled positions when the parameter was varied across its specified range of values, provided a way of ranking the relative importance each parameter (last column in Table 4.7). This revealed that the NAIS model was most sensitive to wind direction, ocean current direction, and keel depth.

Figure 4.16 illustrates the differences in distance error between the base case hindcast for each level of perturbation and at each time step. The model sensitivity for each individual parameter is described in more detail in the following subsections through visual inspection of the resulting modelled iceberg tracks, and with reference to the comparisons of model skill provided in Table 4.7 and Figures 4.16.

Table 4.7 Model input parameters and environmental driving forces examined in the sensitivity analysis, including the range of values and perturbation intervals used.

Input Parameter	Range	Interval	Unit	Mean Deviation (km)	Rank
Iceberg properties					
Waterline length	±50%	25%	m	7.5	11
Keel depth	±50%	25%	m	21.32	4
Coefficients					
Drag coefficient of water	0.5-2.5	0.5	dimensionless	17.33	5
Drag coefficient of air	0.5-2.5	0.5	dimensionless	8.92	9
Environmental forcing data					
Wind direction	±60°	30°	degrees	28.87	1
Wind speed	±50%	15%	m s ⁻¹	16.74	6
Ocean current direction	±60°	30°	degrees	26.22	2
Ocean current speed	±50%	25%	m s ⁻¹	12.24	8
Significant height of wind waves	±50%	25%	m	4.53	12
Direction of wind waves	±60°	30°	degrees	7.9	10
Significant height of swell waves	±50%	25%	m	13.75	7
Direction of swell waves	±60°	30°	degrees	24.76	3

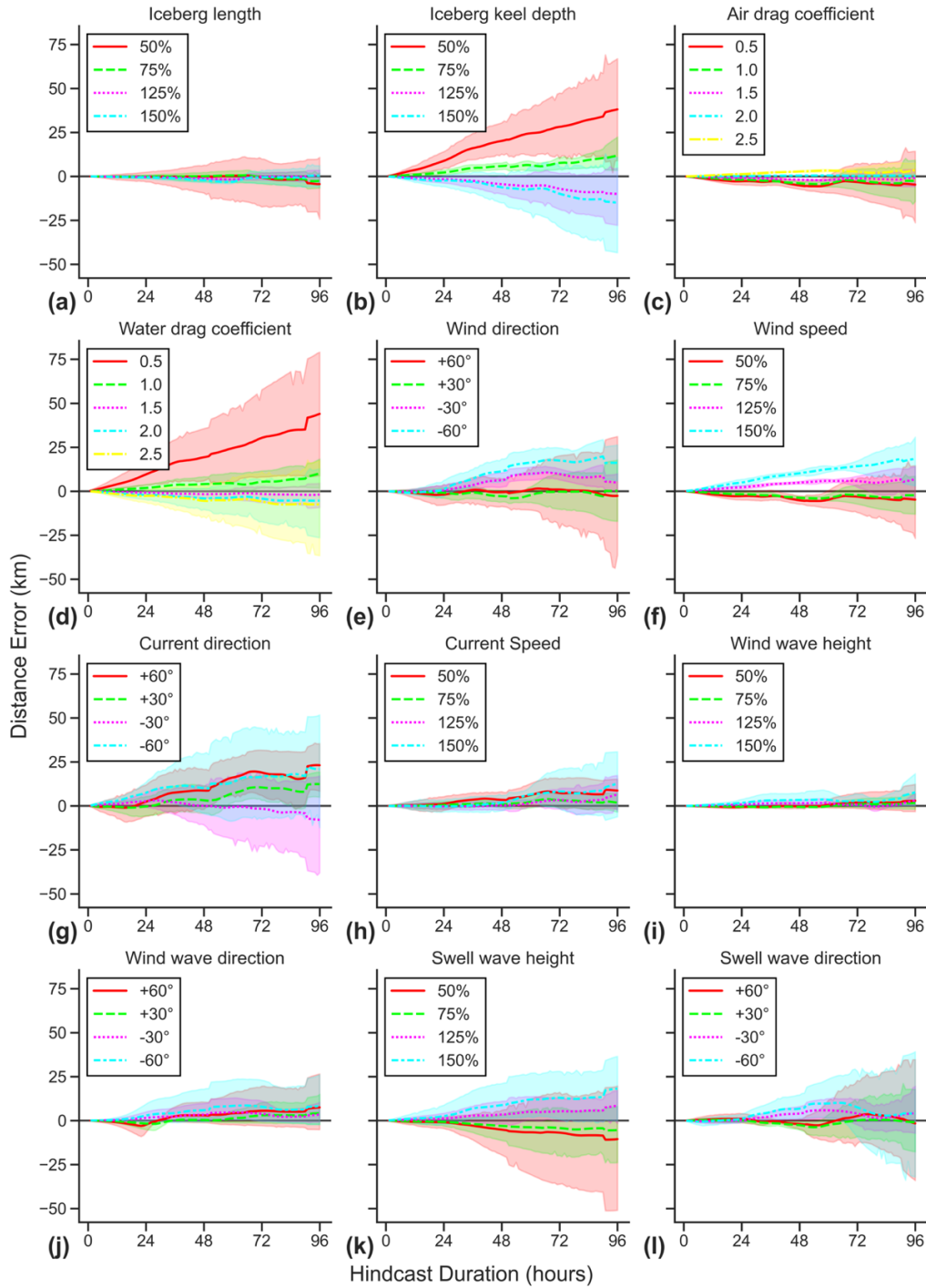


Figure 4.16: Pairwise comparisons of distance error between base case hindcast and perturbation levels ($n = 6$) calculated at each hourly time step for all hindcast simulations of iceberg drift used to assess the sensitivity of the NAIS model. Input parameters: a) iceberg length, b) iceberg keel depth, c) air drag coefficient, d) water drag coefficient, e) wind direction, f) wind speed, g) ocean current direction, h) ocean current speed, i) significant height of wind waves, j) direction of wind waves, k) significant height of swell waves, l) swell wave direction. Changes in wind and ocean current direction is to the left when positive and to the right when negative. Shading indicates 95% confidence interval.

4.3.1 Iceberg waterline length

The model sensitivity to changes in iceberg waterline length is addressed in this section. it should be noted that changes in iceberg length did not alter the model's calculations of iceberg keel geometry, which was manually specified for each iceberg (see Section 3.4.2). Figure 4.16a shows that the model results were insensitive to changes in iceberg length. Visual inspection of the resulting drift tracks (Figure 4.17) revealed that the drift direction and shape of the iceberg track were not considerably affected. However, greater iceberg length values did result in slightly shorter iceberg tracks. Model performance in terms of the distance error for all iceberg tracks showed a slight trend of improved performance with increasing iceberg length. Interestingly, the 50% iceberg length modifier shows as having the greatest variability in distance error across all time steps. This can most likely be explained by differences in the distance error for iceberg F, where the 50% iceberg length was the only modifier that caused the modeled track to remain closer to the observed iceberg track, resulting in distance error values after 48 hours that were 20-30 km less than other hindcast simulations (Figure 4.17f).

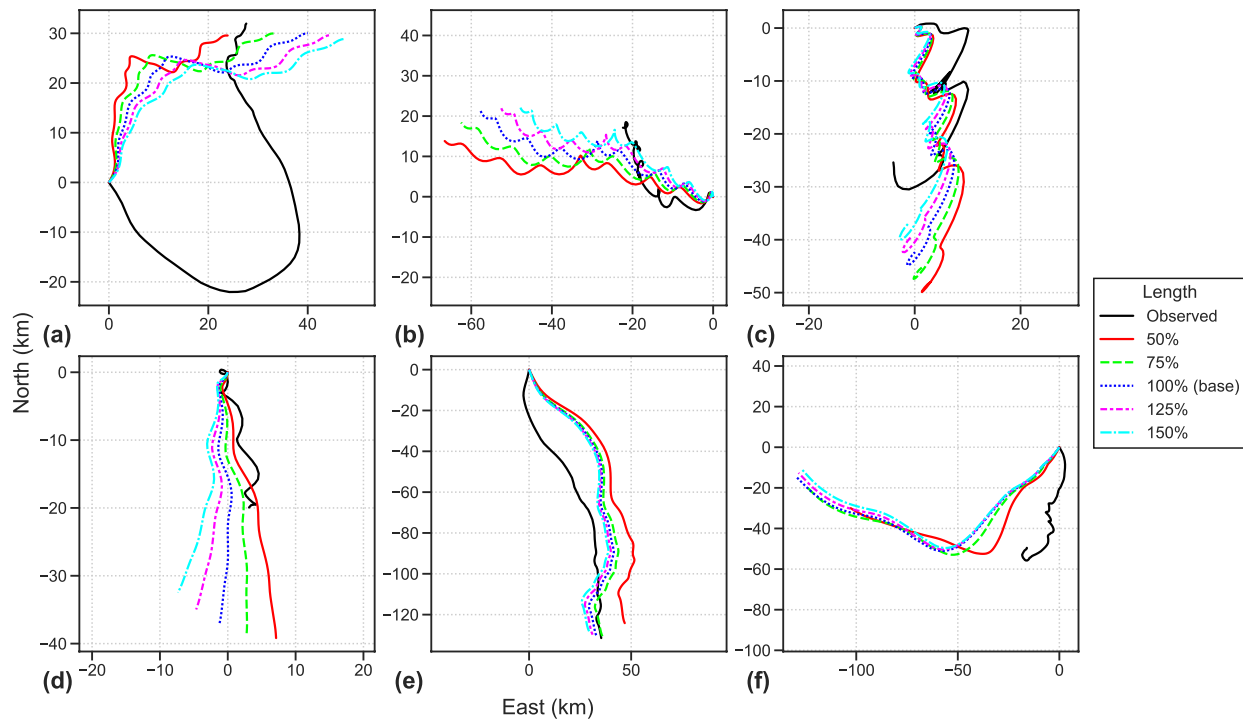


Figure 4.17: Observed and modelled iceberg drift tracks illustrating the sensitivity of the NAIS model to changes in iceberg waterline length. Observed base values: (a) 250 m, (b) 245 m, (c) 420 m, (d) 145 m, (e) 134 m, (f) 127 m.

4.3.2 *Keel depth*

Keel depth base values were estimated using the relationships between sail height and iceberg length outlined in Section 3.4.2. Figure 4.16b shows that the model results are considerably more sensitive to changes in keel depth compared to iceberg length. Visual inspection of the results in Figure 4.18 shows that changes in keel depth did not substantially affect the overall drift direction, or the shape of the iceberg tracks produced by the model. However, the distance travelled by the icebergs varied considerably between different keel depth perturbations. Decreasing the keel depth resulted in the icebergs drifting further than when their keel depth was increased. For example, when using a 50% keel depth, hindcast simulations of icebergs D, E and F resulted in cumulative distances that were greater than the 150% keel depth by a factor of two. Interestingly, when a 50% keel depth was used, some of the looping motion seen in modelled tracks for icebergs B and C appeared to be damped. In terms of model performance, the 125% and 150% keel depth modifiers resulted in lower distance error at each time step, which became more pronounced beyond a hindcast period of 24 hours. When examining the distance error on a track-by-track basis (Figure 4.18), errors were lowest for all icebergs at all timesteps using the 125% and 150% keel depth modifiers, except for iceberg E, which achieved the lowest distance errors using the original keel depth base value.

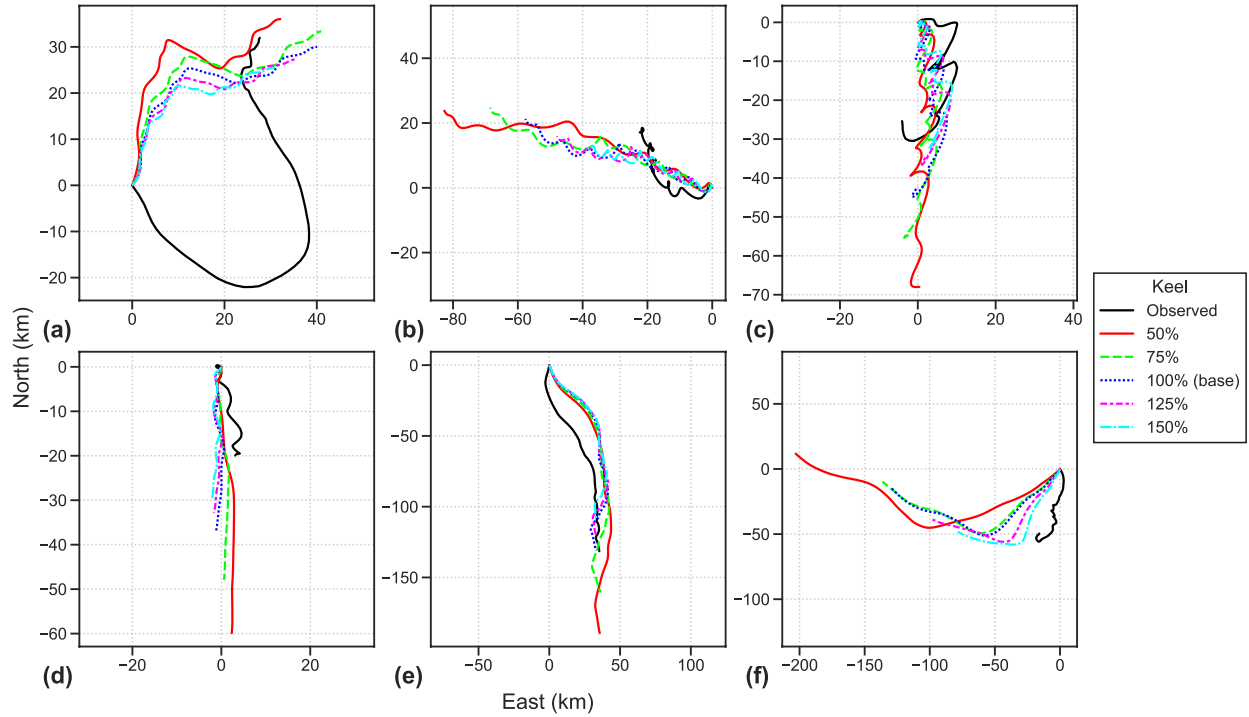


Figure 4.18: Observed and modelled iceberg drift tracks showing the sensitivity of the NAIS model to changes in iceberg keel depth. Observed base values: (a) 75 m, (b) 75 m, (c) 50 m, (d) 105 m, (e) 60 m, (f) 27 m.

4.3.3 Air drag coefficient

Air drag coefficients (C_a) ranging from 0.5-2.5 were assessed, with the results in Figure 4.16c showing that the NAIS model was relatively insensitive to perturbations of this parameter. While the resulting drift tracks (Figure 4.19) showed that neither the drift direction nor the shape of the iceberg track were altered, hindcasts using the highest value of $C_a = 2.5$ were observed to produce iceberg tracks that had an average cumulative distance 4.5% greater than the base case. Conversely, hindcasts using $C_a = 0.5$ resulted in an average cumulative distance that was 13.7% less compared to the base case hindcast. This is expected as higher values of C_a cause a greater influence of wind on the modelled iceberg drift. In terms of model performance, the distance error values calculated at each time step were shown to closely co-vary throughout the entire 96-hour hindcast period. The results in Figure 4.16c also indicate that there was little variability between iceberg tracks, but there was a slight trend of improving model performance with decreasing air drag coefficient values. When examining the distance error on a track-by-track basis (Figure 4.19), the lowest error values were achieved using $C_a = 0.5$ for icebergs B, C, D and F, and $C_a = 2.5$ for iceberg A.

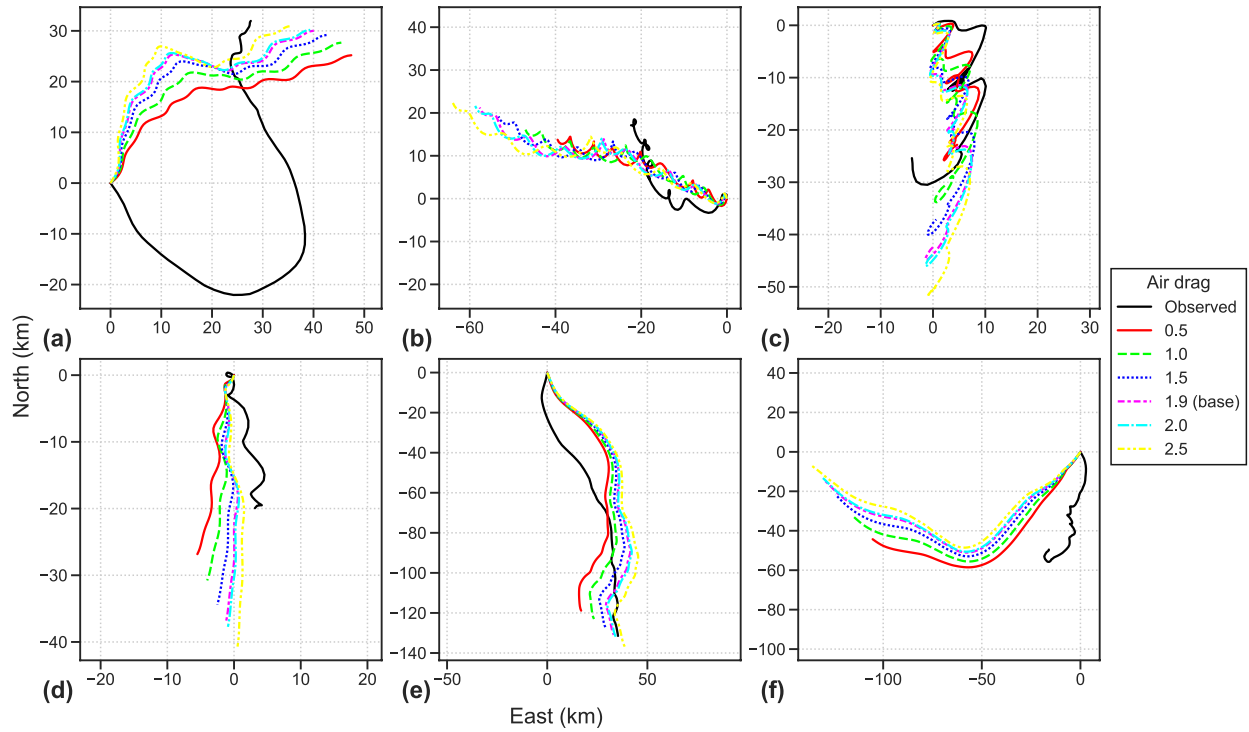


Figure 4.19: Observed and modelled simulations of iceberg drift showing the sensitivity of the NAIS model to changes in air drag coefficient.

4.3.4 Water drag coefficient

Values of the water drag coefficient (C_w) ranging from 0.5-2.5 were tested (Figure 4.16d), with the results showing that the model is considerably more sensitive to perturbations in the water drag coefficient compared to the air drag coefficient. Visual inspection of the resulting drift tracks (Figure 4.20) show that the drift direction and shape of the iceberg track generally remained the same except when using a value of $C_w = 0.5$. Hindcast simulations using this value resulted in a slightly different shape and direction than the simulations using other values for C_w for icebergs B and D. C_w values larger than the base value of 1.3 were shown to decrease the length of all modelled iceberg drift tracks. This is opposite to what was expected, as higher values of C_w should cause a greater influence of ocean currents on the modeled iceberg drift and push icebergs further along their trajectory. In terms of model performance, a value of $C_w = 2.5$ generally produced the lowest distance error for all time steps beyond 24 hours, and C_w values larger than the base value of 1.3 were observed to perform better overall. The results in Figure 4.16d show a slight trend of improving model performance with increasing values of C_w . The distance errors for each hindcast

simulation (Figure 4.20) show that the best results were achieved with a water drag coefficient of 2.5 for all icebergs except iceberg E. Values of C_w less than 1.0 (i.e., 0.5) appeared to introduce instability into the model.

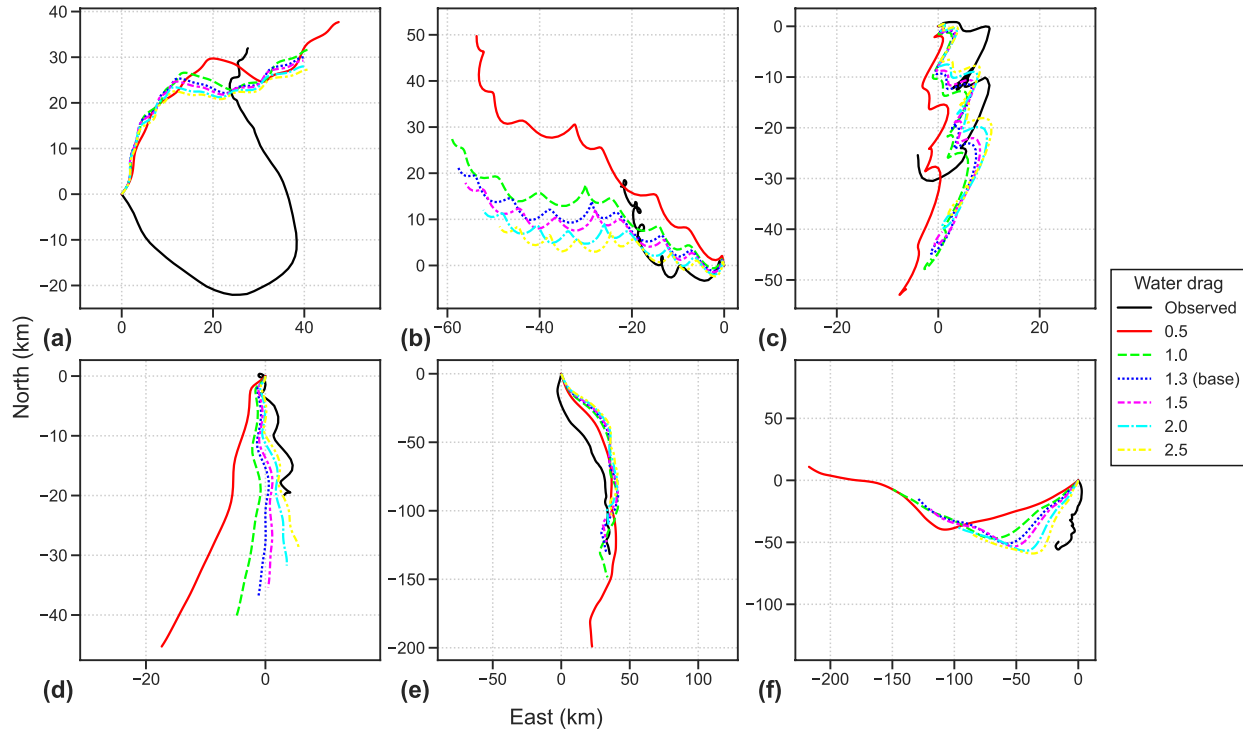


Figure 4.20: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in the water drag coefficient.

4.3.5 Wind speed & direction

Figure 4.16e shows the sensitivity of the model results to changes in wind direction, which highlights the importance of having accurate environmental input data during operational hindcast simulations of observed iceberg drift. The resulting drift tracks (Figure 4.21) show that the drift direction and, in many cases, the shape of the iceberg track were substantially affected by wind direction perturbations. When the wind direction was deflected to the left (i.e., by -30° and -60°), drift was observed to be pushed to the left of the base trajectory for all icebergs. Conversely, when the wind direction was deflected to right (i.e., by $+30^\circ$ to $+60^\circ$), the iceberg drift was pushed to the right of the base iceberg trajectory. This is expected behaviour based on the resulting wind vectors. In many cases, wind direction resulted in considerable changes in cumulative drift distance (e.g., icebergs A, C, F), although no clear pattern in the magnitudes of drift distance differences

was observed. This is likely due to the drift being largely dependent on the wind direction at the time and location of each hindcast simulation. Despite the variability in iceberg drift direction, model performance in terms of distance error was not considerably affected by perturbations in wind direction. When examining the distance errors for each hindcast simulation (Figure 4.21), icebergs A, B, D and E were observed to closely co-vary for all perturbations of wind direction.

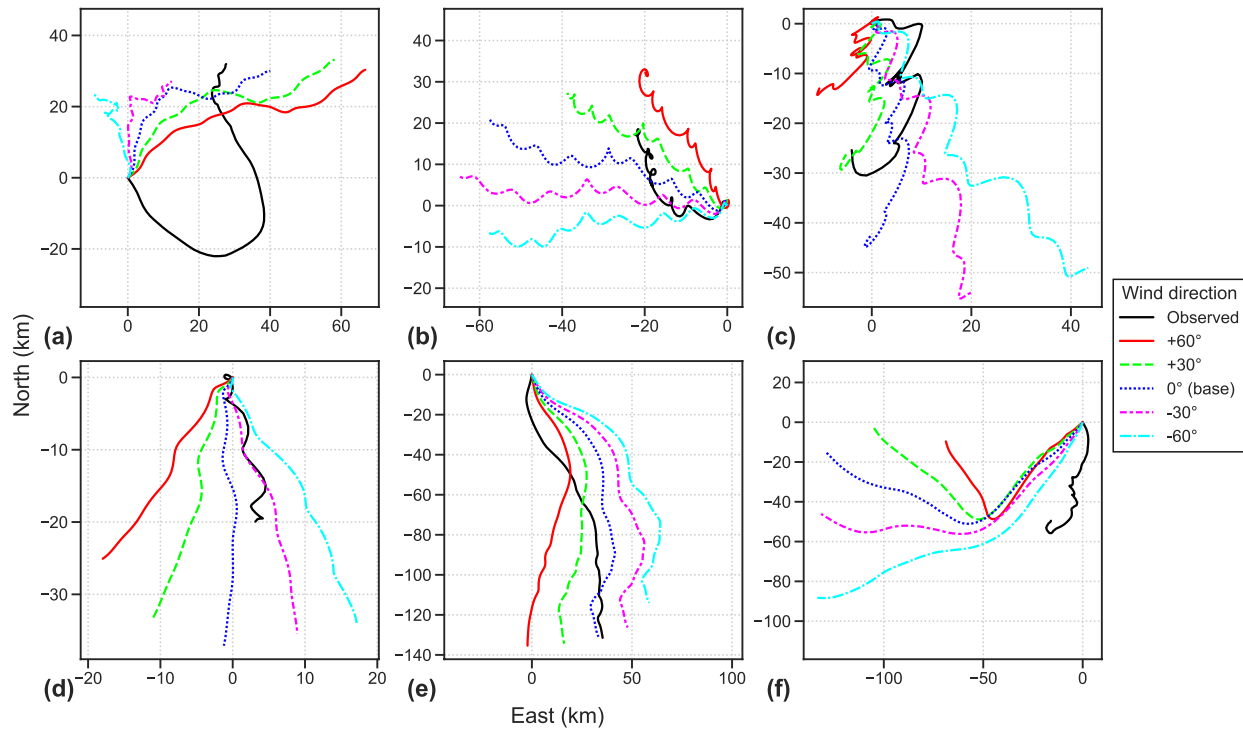


Figure 4.21: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in wind direction.

The results in Figure 4.16f show that the model is somewhat insensitive to perturbations of wind speed. The resulting drift direction or shape of the iceberg tracks (not shown) were not considerably affected. However, hindcast simulations using higher wind speeds produced longer iceberg tracks for all icebergs, except iceberg A. This is expected as higher wind speed values cause a greater influence of wind on the modelled iceberg drift. In terms of model performance, the distance error values calculated at each time step closely co-vary throughout the entire 96-hour hindcast period. The results in Figure 4.16f also show a slight trend of improving model performance with decreasing wind speed. When examining the distance error on a track-by-track basis, the best results were achieved using a wind speed value of 50% for all icebergs except iceberg E, which achieved the lowest distance error using the base wind speed values.

4.3.6 Ocean current direction & speed

The results in Figure 4.16g show that the model was very sensitive to changes in the direction of ocean currents. This again emphasizes the importance of having accurate environmental input data during operational hindcast simulations of iceberg drift. Visual inspection of the model results in Figure 4.22 shows that the drift direction and shape of iceberg track were considerably affected by changes in current direction. Except for iceberg E, drift was observed to be pushed to the right of the base trajectory for all icebergs when the current direction was deflected to the right. Similarly, when the direction was deflected to the left, iceberg drift deviated to the left. Based on the resulting ocean current vectors, this behaviour was anticipated. Changes in current direction of 60° (i.e., left or right) also exhibited the greatest overall impact on the direction of the iceberg drift., particularly for Icebergs A and E. The distance errors for each hindcast simulation exhibit considerable variability as the current direction is perturbed (Figure 4.22). Best overall model performance is achieved when using base current direction values.

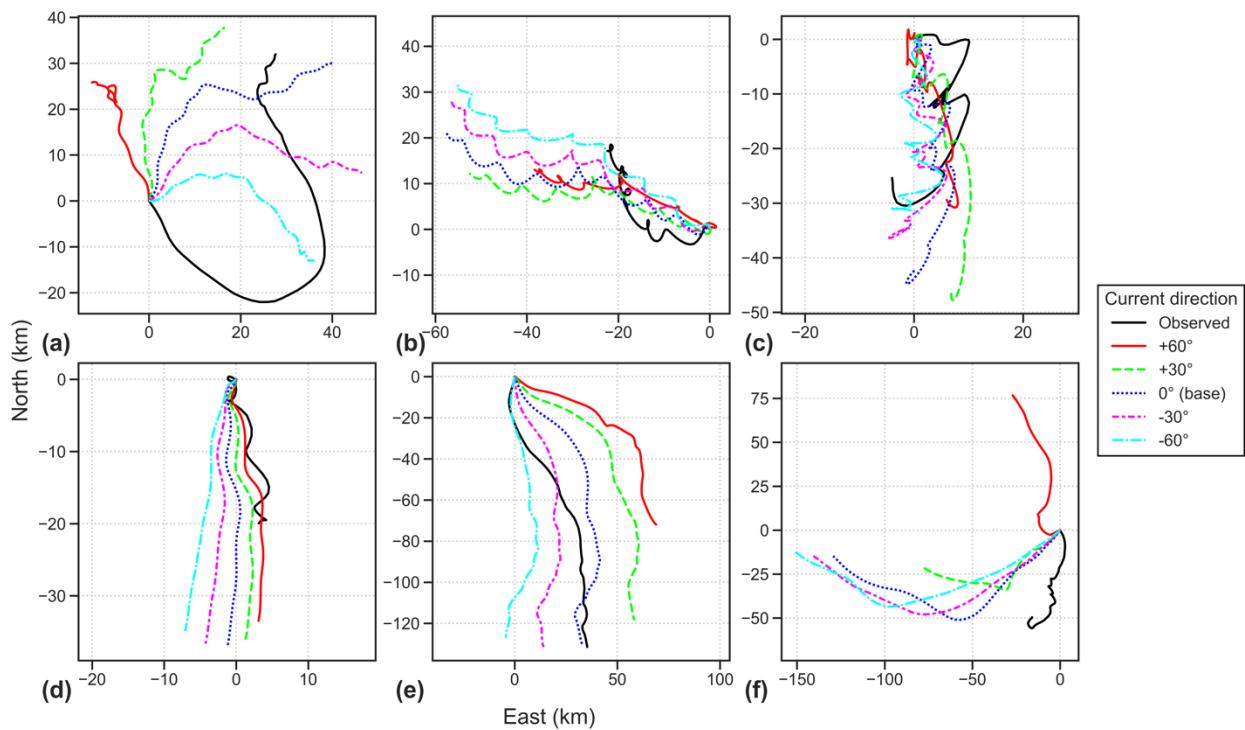


Figure 4.22: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in ocean current direction.

The results in Figure 4.16h show that the model is somewhat insensitive to perturbations in ocean current speed. Visual inspection of the resulting drift tracks (Figure 4.23) shows that the

drift direction and shape of the iceberg track for most icebergs was generally unaffected. However, hindcast simulations for iceberg A showed when current speeds were increased by 150%, substantially longer iceberg tracks were produced. This is expected as faster ocean currents cause a greater influence on the modelled iceberg drift. In terms of model performance, the distance error values calculated at each time step closely co-vary throughout the entire 96-hour hindcast period and there was little variability from the base case simulation as current speeds were perturbed. The results in Figure 4.23 also show that overall model performance is best when using base current speed values.

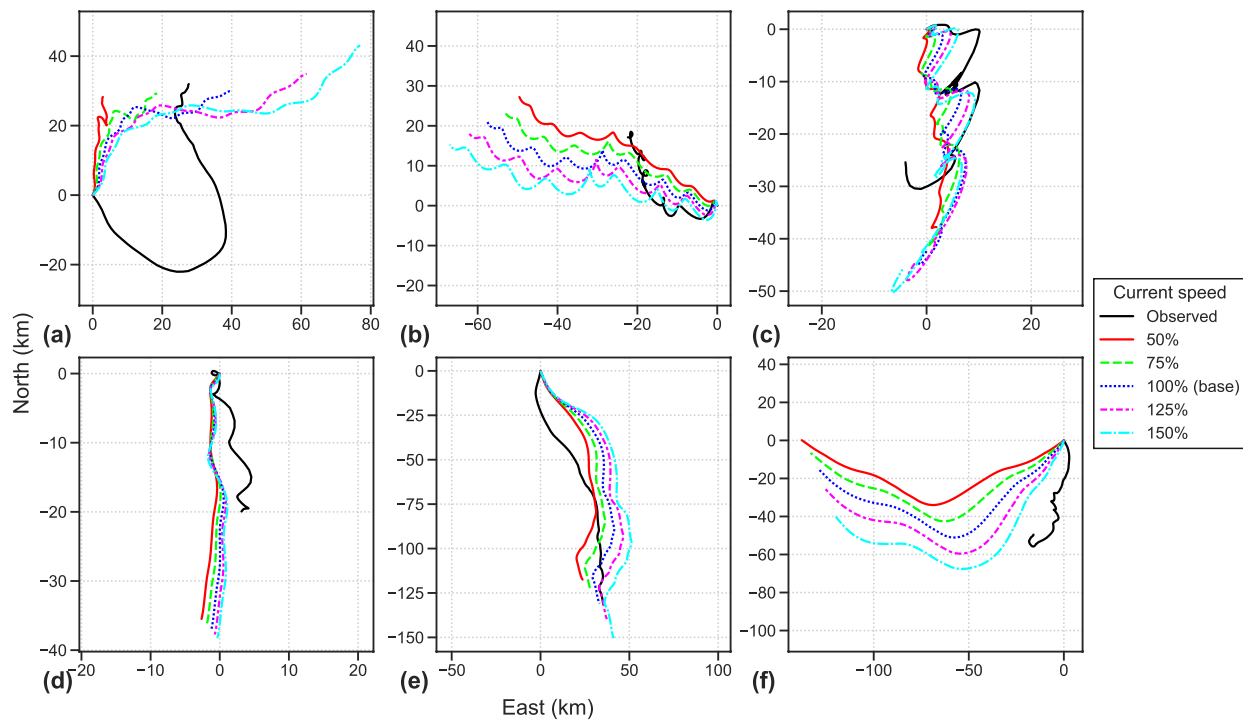


Figure 4.23: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in ocean current speed.

4.3.7 Significant height & direction of wind waves

Based on the hindcast simulations of the observed iceberg drift tracks used in this study, the results in Figure 4.16i reveal that the model is mostly insensitive to changes in the significant height of wind waves. Visual inspection of the modelled iceberg drift tracks did not reveal any substantial changes in drift direction or shape, so they are not plotted here as they are too close to distinguish from each other. Model performance, in terms of the distance error calculated at each time step and for each iceberg track was not appreciably affected by perturbations in wind wave

heights. Values closely co-vary for all wind wave heights and all icebergs, except for iceberg E, which displayed more variability in error.

Similar to the significant height of wind waves, the model is mostly insensitive to changes in direction of wind waves (Figure 4.16j). Visual inspection of the individual modelled iceberg drift tracks shows that the drift direction and track shape were little influenced by perturbations of this variable (Figure 4.24). Hindcast simulations of icebergs A, B, C and E are again too close to distinguish from each other. However, icebergs D and E did show slight changes in drift direction with changes in the wind wave direction. Both icebergs, which moved along a southerly trajectory, drifted further westwards when the wind direction was deflected to the right (i.e., by $+30^\circ$ and $+60^\circ$), while they drifted further eastwards when the direction was deflected to the left (i.e., by -30° and -60°). This is expected behaviour based on the resulting wind vectors. Overall, model performance was not appreciably affected by perturbations in wind wave direction, with distance errors for each hindcast simulation closely co-varying for all perturbations of wind wave heights for all icebergs, except for iceberg E, which displayed more variability (Figure 4.24).

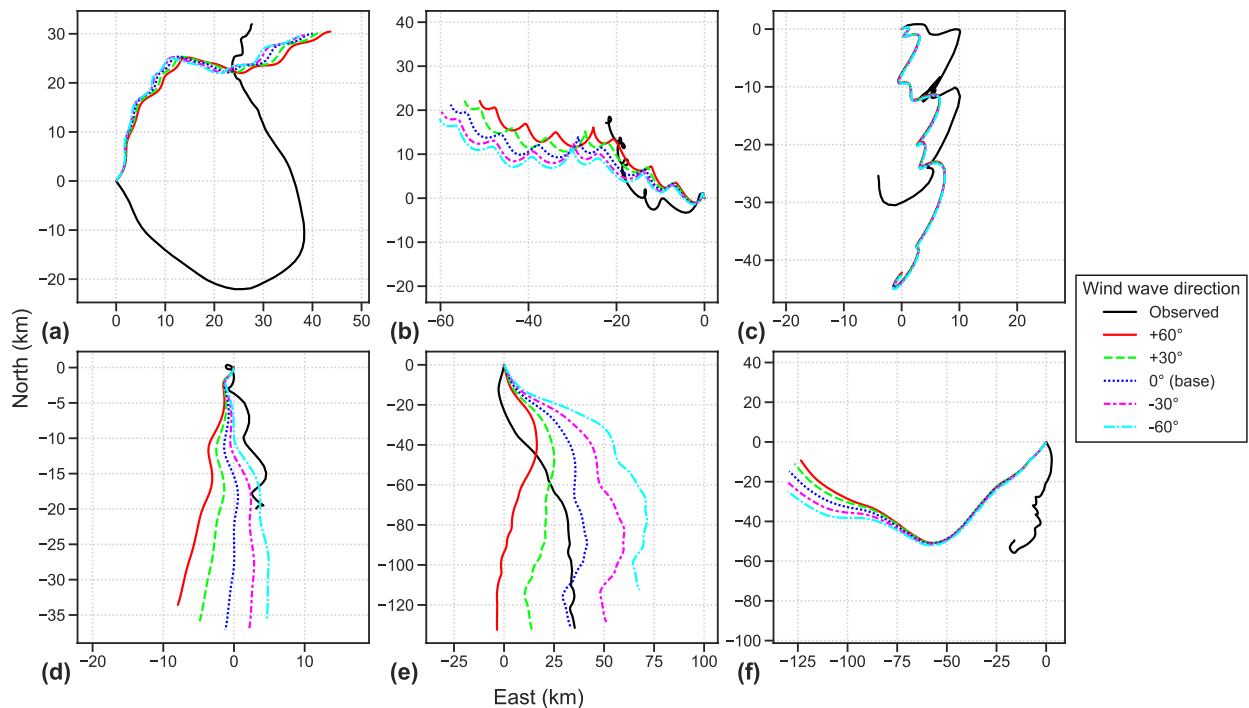


Figure 4.24: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in direction of wind waves.

4.3.8 Significant height & direction of swell waves

The results in Figure 4.16k indicate that the model is somewhat sensitive to changes in swell wave height. Visual inspection of the resulting drift tracks (Figure 4.25) reveals that the drift direction and shape of the iceberg track did not considerably differ between most hindcast simulations. However, slight differences in the cumulative drift distance were observed for icebergs B, D, E and F. As the swell waves heights increased, the icebergs drifted further and resulted in greater distance error values, which is likely the cause of the variability in distance error values at each time step seen in Figure 4.16k. This variability can also be mostly attributed to iceberg F, which like waterline length, had cumulative and distance error values that were substantially different than the base swell height values (Figure 4.25).

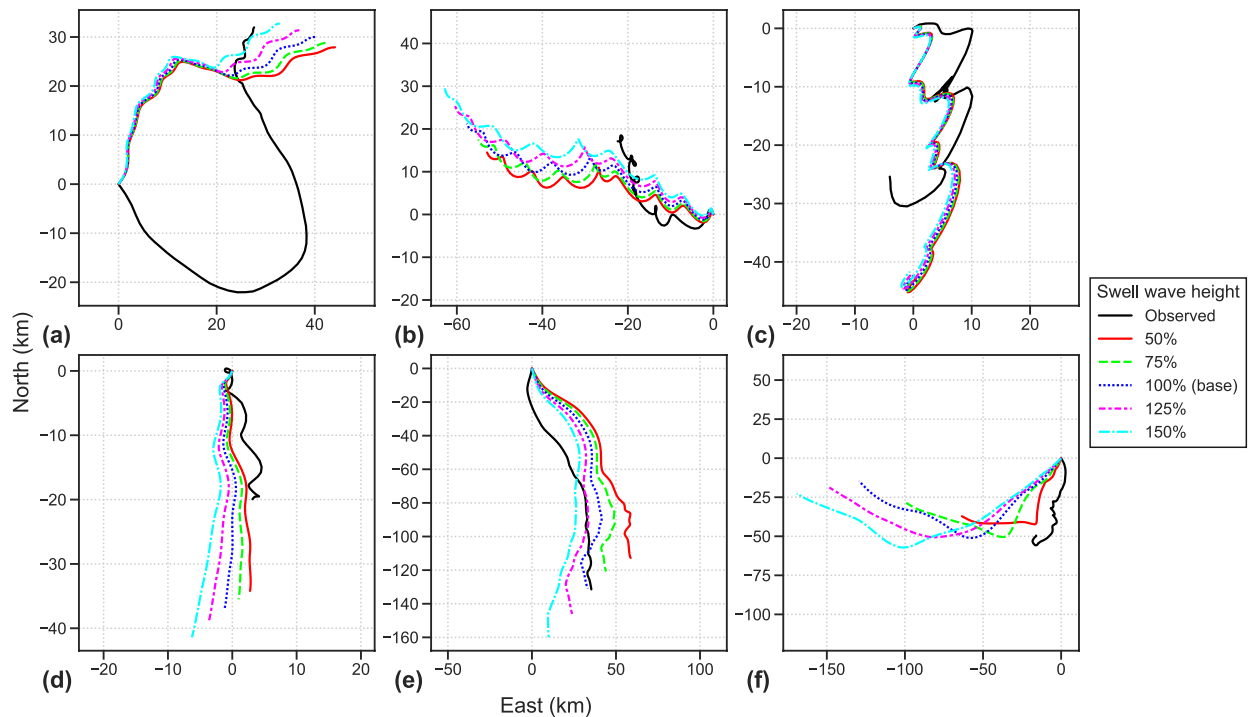


Figure 4.25: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in significant height of swell waves.

The results in Figure 4.16l show that the model is relatively insensitive to changes in the direction of swell waves during the first 48 hours. Visual inspection of the modelled iceberg drift tracks shows that the drift directions and track shapes were mostly unaffected by perturbations of this variable, with hindcast simulations of icebergs A and C too close to distinguish from each other (Figure 4.26). Icebergs D and E co-vary for the first 48 hours of the drift tracks and then

begin to diverge. Iceberg F, as with other parameters, is an outlier with drift tracks that immediately begin to diverge. Iceberg drift was observed to be pushed to the right of the trajectory for all icebergs when the swell wave direction is increased and pushed to the left when it is decreased. Model performance was not considerably influenced by perturbations in swell wave direction. The distance errors for each hindcast simulation also closely co-vary for all perturbations of swell wave direction for all icebergs, except for iceberg E, which displayed considerably more variability in error (Figure 4.26).

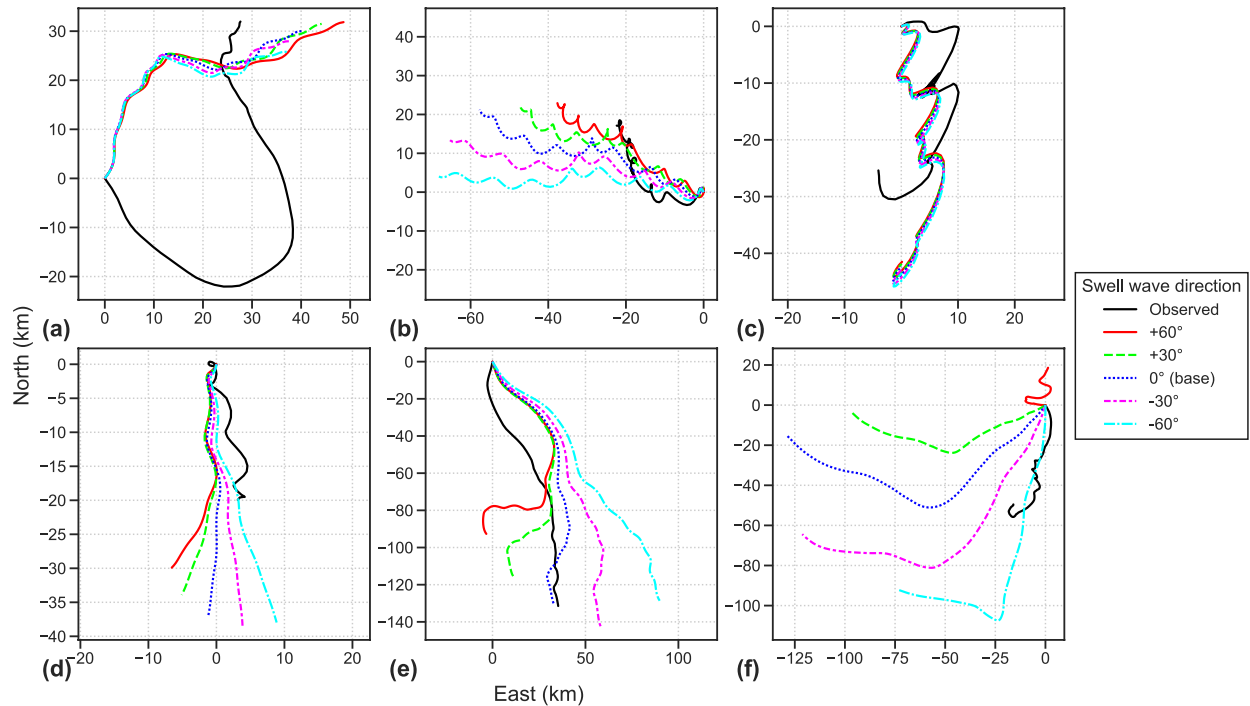


Figure 4.26: Observed and modelled simulations of iceberg drift illustrating the sensitivity of the NAIS model to changes in direction of swell waves.

Chapter 5: Discussion

5.1 Iceberg drift tracking beacons

Development of the Cryologger iceberg tracking beacon began in 2018 with the motivation of creating, and assessing the suitability of, a low-cost, open-source technology for collecting high spatial and temporal resolution iceberg drift data. This has continued during the completion of this thesis, including evaluation of the performance of past Cryologger deployments, making modifications to improve the overall design, and instrumenting additional icebergs in the Canadian Arctic.

5.1.1 Operation

The operational lifespan of an iceberg tracking beacon is typically dependent on two main factors: (1) the battery capacity of the beacon, and (2) the stability of the iceberg (Larsen et al., 2015). The lithium thionyl chloride (LiSOCl_2) battery packs in the Cryologger are intended for use in extreme cold, but the rated capacity of the batteries can drop considerably when exposed to low temperatures and periods of increased power consumption (e.g., during Iridium satellite transmissions) (Clark et al., 2019). As a result, battery capacity was conservatively estimated to be sufficient for 1 year of operation with hourly transmissions. Another potential design limitation was whether the electronic components would operate in extremely low temperatures. The Cryologger was built using industrial-rated electronic components that have an operating range of -40°C to 80°C , but component performance can be degraded below temperatures of -20°C (Tiffin et al., 2012). There is also little information available from manufacturers regarding the effects of frequent temperature cycling on components. These factors represented several unknowns with respect to the viability of low-cost, open-source electronics for use in the harsh Arctic environment.

Despite these uncertainties, the performance of the Cryologger deployments far exceeded expectations, with 2018 and 2019 deployments operating between 310-1187 days, and 331-837 days, respectively (Table 4.1). Battery capacity was not a limiting factor, as evidenced by the performance of beacon 5160, which has reliably transmitted every 3 hours for over 3 years and survived multiple Arctic winters and temperatures frequently below -40°C . These operational lifespans are comparable to, or exceed, the performance of previous iceberg tracking studies in

Canadian waters that have employed several different commercial tracking devices (IIP, 2009; Larsen et al., 2015; Peterson et al., 2009; Peterson & Prinsenberg, 2014). These results provide strong support for the suitability of the electronic components and battery selected for the Cryologger design. However, it should be noted that the LiSOCl_2 battery packs are classed as dangerous goods, which results in higher logistical costs and can present difficulties for shipping (e.g., air cargo only), especially in the Arctic. Therefore, additional research into alternative battery chemistries that are less hazardous and more environmentally friendly is warranted for future designs.

The fate of an iceberg is determined by a number of processes, including rolling, break-up and deterioration (Wagner et al., 2017). The eventual loss of Cryologgers deployed on icebergs was therefore anticipated, considering their dynamic and unstable nature. For deployments in 2018, communication failures were caused by iceberg break-up events that were confirmed for all six icebergs using successive satellite imagery (from sensors such as Sentinel-2 and Landsat-8) centred on the dates of communication loss. From a scientific standpoint, this outcome was ideal, as the beacons were able to monitor the drift of the icebergs over months and years until their eventual demise. In previous studies, the total lifespan of the beacon deployments made off the coast of Newfoundland and Labrador was often measured in days (e.g., Jones & Gudmundsson, 2015; Peterson & Prinsenberg, 2014). Deployments made in 2019 encountered several challenges related to design modifications that were intended to reduce the size, weight, and cost of the Cryologger (Section 4.1.1). These issues indicate that a lighter and smaller form-factor is not necessarily better, as it becomes more susceptible to environmental factors, such as strong winds that can cause the beacon to invert. In this orientation, the beacon becomes more susceptible to water ingress, which can cause it to cease functioning. There is also a trade-off between the robustness of the beacon enclosure and ease of use in the field. While the Nanuk 903 and 905 enclosures have latches that can be opened easily they are only rated for immersion in water up to 1 m deep for 30 minutes, an IP67 (Ingress Protection) rating. To the author's knowledge, there are no commercial off-the-shelf solutions that provide a completely waterproof, but also easily accessible, enclosure. The development of such an enclosure represents another significant area of potential future research.

5.1.2 *Estimates of iceberg morphology*

Previous studies (Barker et al., 2004; Hotzel & Miller, 1983) have shown that the geometry of an iceberg can be adequately described using the iceberg's waterline length. This is advantageous for field studies, as the waterline length is relatively easy to observe compared to other attributes, such as depth below the water. At the time of Cryologger deployment, measurements of the above-waterline dimensions of the iceberg (length and width) were visually estimated. The iceberg's sail height was also approximated using the helicopter's pressure altimeter when landing on the surface or hovering a few metres above it. However, when satellite imagery was used to confirm the dimensions of icebergs, it was discovered that field measurements frequently over-estimated the length of the iceberg, in some cases by up to 200%. This is most likely a result of the difficulty of estimating the scale of an iceberg from the air, as there often no nearby scale references. As satellite imagery is not always available at the time of deployment, or has insufficient spatial resolution to identify the iceberg, this highlights a need for more reliable methods of estimating the physical characteristics of an iceberg at the time of deployment (e.g., laser range finders). In turn, these measurements would allow for more finely tuned empirical equations that can be used to determine an iceberg's sail area, draft, and mass as a function of its waterline length.

5.1.3 *Iceberg drift*

Much of our current knowledge of iceberg drift behavior in Baffin Bay comes from studies performed over 30 years ago (e.g., Marko et al., 1982; Robe et al., 1980; Smith & Donaldson, 1987). Icebergs drifting along the western side of Baffin Bay generally follow the prevailing currents southward. Marko et al. (1982) observed mean iceberg drift speeds between 10 to 30 km d⁻¹ (0.42-1.25 km h⁻¹) along the coast of Baffin Island, and Marko et al. (1994) report typical drift speeds of 15-20 km d⁻¹ (0.62-0.83 km h⁻¹) once an iceberg reaches the Labrador Sea and is carried along the Labrador Current. The results of this study are consistent with the findings of previous studies, with icebergs instrumented in 2018 and 2019 observed to have mean drift speeds ranging from 1-18 km d⁻¹ (0.04-0.75 km h⁻¹). Maximum speeds ranging from 2.44-6.04 km h⁻¹ (>75 km d⁻¹) were recorded for several icebergs in this study (Table 4.1), which far exceed the observed velocities of previous studies in Baffin Bay. However, these velocities were only sustained over short periods of time (i.e., 2-6 hours), and frequently only in specific geographic areas. For

example, beacon 5310 (Figure 5.1) experienced maximum drift speeds of approximately 6.0 km h^{-1} when drifting off the coast of Resolution Island, Nunavut. This iceberg was observed to drift in an oscillating pattern consistent with the semi-diurnal tidal period in the region. These high drift speeds can most likely be attributed to strong surface currents and are supported by Wu et al. (2013), who recorded maximum observed surface currents, including tidal and non-tidal components, as high as 2.0 m s^{-1} (7.2 km h^{-1}) along the Baffin Island shelf in Davis Strait. These measurements provide important information regarding the combined effects of ocean currents, tides, and winds on maximum iceberg drift speeds in a given area. They can also be applied when cleaning iceberg observation data. Typically, a threshold for valid drift speeds is established and all observations exceeding this value are discarded. The collection of *in-situ* observations of iceberg drift can enable a more informed decision regarding the realistic limits of the drift speed of an iceberg.

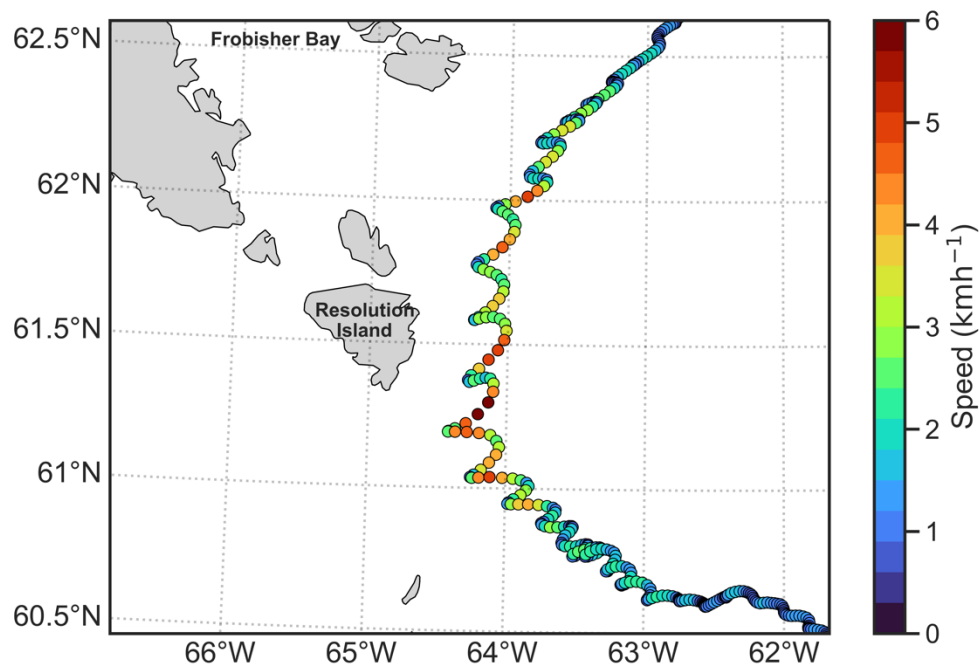


Figure 5.1: Drift of iceberg instrumented with beacon 300434063415110 illustrating maximum drift speeds of 6 km h^{-1} and tidal current effects near Resolution Island, Nunavut between April 16-29, 2019.

Notably, only one of the icebergs instrumented in 2018 and 2019 was observed to reach the Labrador Coast (Figure 4.1). This iceberg, initially instrumented off the east coast of Coburg

Island, remained grounded from August to December 2019 and only began to drift down the coast of Baffin Island after becoming trapped in pack ice. It is believed the winter ungrounding of this iceberg allowed it to survive long enough to drift all the way to the Labrador Coast. Sea ice has been identified as playing a critical role in determining whether an iceberg will survive to more southerly latitudes, by preventing iceberg grounding events and reducing deterioration rates from wave action, and reducing subsequent fracturing and fragmentation along shallow coastal shelves (Crawford, 2013; Marko et al., 1994). Marko et al. (1982) also noted that icebergs able to remain in off-shelf areas during the period of land-fast sea ice regrowth in the Arctic between late August and November have a greater likelihood of drifting southward along the coast of Baffin Island, as the presence of land-fast sea ice reduces the likelihood of entrapment along the coastal shelf. The iceberg instrumented with beacon 5110 took 4 months to drift from Bylot to Resolution islands (~1700 km), which is in agreement with Marko et al. (1982), who estimated a total travel time of 1.5-5 months for this journey. The remaining time from Resolution Island to the coast of Labrador (~1500 km) took 2 months, which agrees with the average drift velocities of Labrador Current noted by Marko et al. (1994).

5.2 Model validation

One of the primary objectives of this study was to validate the NAIS iceberg drift model using *in-situ* observations of iceberg drift from a newly compiled database of iceberg beacon tracks. As previous efforts to validate the model (Carrieres et al., 2001; Kubat et al., 2005) focused on iceberg drift data collected south of 60°N, this study also set out to address a critical knowledge gap regarding the model's ability to operate in regions north of 60°N. Through quantified comparisons of model performance, the suitability of the model for use in locations beyond its current operational area were assessed. In addition, several questions beneficial to end-users, such as identifying the longest duration that forecasts can be relied upon, and in which geographic regions the model provided the most accurate forecasts of iceberg drift, were explored.

5.2.1 Bias of iceberg drift observations

Observations from the iceberg beacon database provided a valuable source of *in-situ* iceberg drift data from Canadian waters. Ideally, detailed drift trajectories for a wide variety of iceberg shapes and sizes would be used for model validation. However, the database is strongly

biased towards larger, generally flat-topped icebergs, with 71% of icebergs in the database classified as tabular and 6% as blocky. This bias is primarily due to logistics and safety as commercial iceberg tracking devices are typically deployed by helicopter (e.g., Larsen et al., 2015; Sulak et al., 2017; Sutherland et al., 2014) and therefore require a large, stable platform to land. The high cost of commercial tracking devices and helicopter flight time also limits the number of beacons available for deployment. Therefore, preference is given to larger icebergs to maximize the lifespan of the tracking device until the iceberg rolls or breaks up. A consequence of this bias is that the drift characteristics of small icebergs, and other iceberg shapes, is not as well understood.

The selection criteria used in this study (Section 3.2.1) also introduced spatial and temporal bias to the iceberg drift tracks used for NAIS model validation. Many of the selected tracks were collected in northern Baffin Bay and Kane Basin, or along the Labrador Coast and Grand Banks (Figure 3.4), resulting in a paucity of iceberg observations between 55°N and 70°N. While model validation results derived from these data should be representative of the region in which they were collected, they may not be suitable for characterizing iceberg drift in different areas (e.g., across the entire Baffin Bay region). A strong seasonal bias was also introduced during the data processing steps (Section 3.2.2) as iceberg tracking beacons were primarily deployed during the summer, which meant that most of the iceberg tracks ended up being from the summer and fall since they were trimmed to a maximum duration of 28 days from their deployment date (Table 4.6). Future studies may look at selecting data from time periods much further along each iceberg track, although if this was done it would require the use of high-resolution satellite imagery to quantify how the size characteristics of icebergs change over time so that accurate inputs can be provided for the iceberg drift model. While requiring substantially more effort, this would allow for a wider spatial and temporal coverage for future model validation studies.

5.2.2 *Model performance*

For the purposes of this study, the distance error between observed and modelled positions provided the primary metric used to assess the performance of the NAIS iceberg drift model (Section 3.5.1). However, it should be noted other metrics can be used to assess predictions of iceberg drift, such as those relating to drift direction or velocity (e.g., Andersson et al., 2018; Carrieres et al., 2001; Mongroo & Li, 2010; Murphy & Carrieres, 2010). Additionally, while model

validation was performed using multiple sources of ocean currents, a more detailed comparison of model performance based on different ocean current models is explored in Section 5.3.3.

When assessing the skill of an iceberg drift model, it is important to consider what is acceptable model performance. In a preliminary validation study of the NAIS model by Carrieres et al. (2001), hindcasts of the observed drift of 17 icebergs located off the east coast of Canada resulted in an RMSE of approximately 18 km after 24 hours, which increased by 12 km d⁻¹ over a 96-hour hindcast period. In a later study by Murphy & Carrieres (2010), hindcasts of the observed drift of 137 icebergs collected between 2002-2007 from the Grand Banks of Newfoundland produced a 24-hour RMSE of approximately 20 km, which increased by 11 km d⁻¹ over a total hindcast period of 96 hours. These are typical values when making predictions of iceberg drift and are generally consistent with the results of this study. For both the 2009-2019 and 2017-2019 hindcasts periods used here, the 24-hour RMSE ranged between 19-22 km, and increased at average rates of 11-13 km d⁻¹ (Figures 4.6, 4.9). These RMSE results are promising, as they indicate that over a large set of hindcasts the modelled positions more closely resemble the observed positions. However, it is important to consider that these results are aggregated statistics of modelled drift for iceberg observations that differ widely in space and time.

The usefulness of the NAIS model predictions of iceberg drift for operational use is an important aspect of this study. While the RMSE results indicate that the validation produced comparable results to previous drift modelling studies, it is also important to consider the performance of individual modelled iceberg tracks. Figures 4.5 and 4.8 illustrate the final distance error of hindcasts during both 2009-2019 and 2017-2019 hindcast periods. It is encouraging to note that the majority of hindcasts had final distance errors that were less than 50 km after 96-hours of drift. However, it is important to acknowledge that some hindcasts were extremely inaccurate (e.g., > 150 km), which warrants further investigation into the potential causes of such outliers. While 96-hours was selected as a maximum hindcast period, in many cases, the 24-hour drift error can also provide an important metric when determining iceberg hazards (e.g., for offshore oil platforms). Overall, the NAIS model produces good results over a 24-hour period, irrespective of location, with mean distance errors of 15-18 km (Tables 4.2, 4.4). Figures 4.5 and 4.8 also show that as the simulation time increases, so too does the variability, so model results beyond 48 hours should be considered less reliable.

When considering the performance of the model in terms of its tendency to over- or under-estimate iceberg drift, it is notable that the majority of hindcast simulations (i.e., >70%) over-estimate cumulative drift distances (Figures 4.5, 4.8). One possible explanation of this behaviour may be due to how environmental forcing data, such as ocean currents, are used to calculate the driving forces acting on the iceberg and the inability of the model to capture short-term iceberg motion. Many of the observed iceberg tracks used in this study (Appendix B) exhibit irregular behaviour likely caused by several factors, such as tidal and inertial loops, which act over short time scales to influence the drift of the iceberg (Robe et al., 1980; Andersson et al., 2018). During the NAIS model's predictions of iceberg drift, forces acting on the iceberg are calculated every 15 minutes. However, because environmental inputs typically have coarser temporal resolutions, interpolation methods must be used, meaning that much of the short-term variability in drift is likely not well represented. The number of hindcasts that over-estimate drift distance and the temporal resolution of the ocean currents used in this study seems to support this. RIOPS, CECOM and GLORYS, which have temporal resolutions of 1-hour, 3-hour, and 24-hour, respectively, overestimated drift in 70%, 80%, and 83% of the simulations. Similar behaviour was observed by Kubat et al. (2005), who found that sharp and irregular movements in observed iceberg tracks were not captured in the NAIS model output. As it is possible to configure the NAIS model to interpolate the environmental inputs less frequently, this represents a potential area for future study to determine whether the model could be adjusted to reduce the likelihood of over-estimating drift.

5.2.2.1 Model performance vs. iceberg length

The performance of an iceberg drift model can be influenced by several factors, including the morphology of the iceberg and the environmental driving forces (Smith, 1993; Wagner et al., 2017). The iceberg waterline length warrants further analysis as it is one of the most important physical characteristics of an iceberg, and often the only measurement available for modelling studies. The iceberg length can also be used by the model to determine the keel depth and iceberg mass (Barker et al., 2004), although these measurements were manually specified in this study.

Figure 4.11 illustrates the relationship between iceberg length and the cumulative travel distance of icebergs used in this study after 96 hours of drift. Based on these observations, it is evident that shorter icebergs (i.e., <300 m) experience the greatest variability in drift distance, ranging between 50-200 km over a 96-hour period. Given this wide drift distance range, it was

expected that the model would encounter greater difficulty when predicting the drift of these smaller icebergs, and therefore larger distance errors would be expected. This was confirmed by the results shown in Figure 4.12, which illustrates that hindcasts from both the 2009-2019 and 2017-2019 periods exhibit a similar pattern of decreasing RMSE, and therefore improving model skill, as iceberg length increases. It should be noted that Figure 4.12 also considers all hindcasts ranging from 24-96 hours, which may account for some of the small RMSE values associated with shorter simulations. The trend in performance is most evident in the 2017-2019 hindcasts, which due to data constraints, do not include icebergs longer than 500 m. Here, we can see that icebergs shorter than 200 m experience greatest variability in RMSE, while those longer than 300 m experience half as much variability in RMSE. These results that some runs are representative but many are not, and points to some process or characteristic relevant only to small icebergs that is resulting in the poorer model performance.

This observed trend of improved model performance for longer icebergs can likely be attributed to the relationship between iceberg length and keel depth, and the controlling effects these properties have on the resulting influence of ocean currents acting on the iceberg. The keels of shorter icebergs are mostly found within the upper ocean layers, which can be strongly influenced by wind, while longer, deeper-keeled icebergs have much of their surface area below the influence of local winds and are instead primarily influenced by deeper ocean currents, and the effects of Ekman spirals (Mountain, 1980). This is supported by Kubat et al. (2005), who found that when the NAIS model was driven using only ocean current velocities from the upper surface layer, significant errors in the predicted drift tracks were observed. In a study of drift modelling in the Barents Sea, Eik (2009) also found ocean currents of equal magnitudes but in opposing directions between 3 m and 100 m depth layers. It is believed the longer, deeper-keeled icebergs used in this study (Figure 3.12), are less influenced by erratic surface currents and therefore the drift is more predictable and less difficult to model. This hypothesis appears to be confirmed when the RMSE is plotted as a function of the keel depth (Figure 5.2). Here, we can observe a very similar trend in RMSE of increasing model performance with increasing keel depth. Thus, the iceberg length-keel relationship and influence of surface currents are assumed to be primary contributing factors to the observed trends in model performance, which also underlines the importance of properly constraining this physical characteristic when deploying iceberg trackers and performing drift modelling studies.

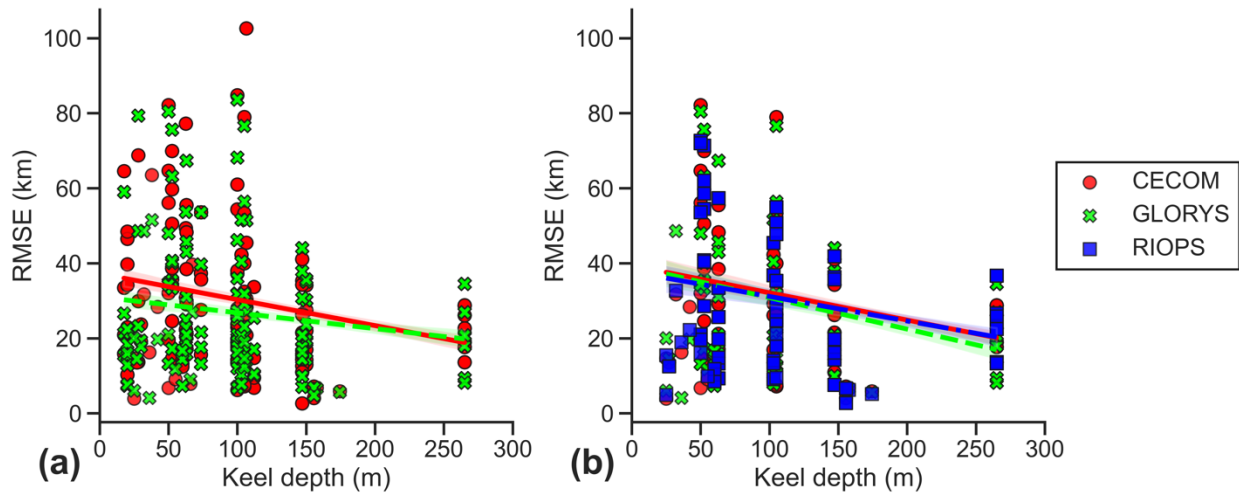


Figure 5.2: RMSE as a function of iceberg keel depth for all hindcast simulations of iceberg drift using: (a) CECOM and GLORYS modelled ocean currents for 2009-2019; (b) CECOM, GLORYS and RIOPS modelled ocean currents for 2017-2019. Regression lines and shaded 95% confidence intervals are shown for each modelled ocean current.

5.2.2.2 Spatial variability of model performance

The bias in the use of iceberg tracks from primarily 45-55°N and 70-80°N (addressed in Section 5.2.1), makes it difficult to determine if spatial trends in NAIS model performance are present across the entire 45°N-80°N latitude range of the study area. However, the results shown in Figure 4.13, which illustrates the RMSE for each iceberg track as a function of the starting latitude, provides several key takeaways. Most importantly, the variability in RMSE is similar at 55°N and 75°N for both 2009-2019 and 2017-2019 hindcast periods. For the relatively few observations that exist, the model also consistently had some of the lowest RMSE values between 60°N-70°N. This seems to indicate that model performance is not latitude dependent, indicating that the model is suitable for use at more northerly latitudes than the <60°N range it was developed for. The most likely explanation for this behaviour is that the performance of the model is constrained by the quality of the environmental input data, which can vary greatly in space and time (Eik, 2009). For the good performance around 60°N-70°N, Figure 3.4 shows that these tracks are primarily found along the southeast coast of Baffin Island, where the BIC is likely more predictable and less difficult for ocean current models to simulate. Finally, the model was observed to consistently perform best between 45°N-50°N. This result is not surprising, as this encompasses the operational area of the NAIS model, and most efforts to improve the model have taken place

in this region (e.g., Barker et al., 2004; Kubat et al., 2005). However, it is noteworthy as to how quickly model performance degrades north of 50°N. Figure 4.13b shows a clear decline in model performance at 55°N, with RMSE two to three times greater than at lower latitudes. This behaviour is consistent with a study by Murphy & Carrieres (2010), which found a decline in the accuracy of the forecasts north of 50°N. The cause is not immediately known; however, it may be attributable to factors such as the spatial variability and the errors associated with wind and ocean current environmental forcing data. For example, Peterson & Prinsenberg (2014) found that iceberg velocities on the Labrador Shelf were affected by spatially variable currents other than the Labrador Current, such as localized eddies.

Figures 4.14 and 4.15, despite being based on a limited number of observations, also provide insights into model performance by illustrating the spatial variability of 24-hour RMSE. Most notably, model performance for both 2009-2019 and 2017-2019 hindcast periods is comparable between northerly (i.e., above 70°N) and southerly (i.e., below 60°N) latitudes, which again lends support for the use of the NAIS model at higher latitudes. An interesting aspect of these results is the disparity in variability of RMSE between northern Baffin Bay (~75°N), compared to Nares Strait (~77.5°N) (Figure 4.14a-b). One possible reason for this difference may be due to the complex system of ocean currents in northern Baffin Bay. Here, cold fresh Arctic waters from Nares Strait and Lancaster Sound merge into the BIC, with contributions from the warmer, saltier WGC (Münchow et al., 2014). Even though the dominant flow is southward, ocean currents in this region can be at times highly variable (Yao & Tang, 2003). As a result, currents in the region may be poorly represented by ocean current models, which in turn, may lead to less accurate predictions of iceberg drift.

5.2.3 *Comparison of modelled ocean currents*

One of the goals of this study was to investigate the potential for improvement to the NAIS iceberg drift model through comparisons of model performance using different ocean current models. This is especially relevant, as previous studies have found ocean currents to have the most pronounced effect in determining the drift of an iceberg (e.g., Smith & Banke, 1983; Eik, 2009; Keghouche et al., 2009; Zeinali Torbati et al., 2020). While the results in Figures 4.4 and 4.7 illustrate the considerable variability in distance error for hindcasts produced using ocean currents

from CECOM, GLORYS and RIOPS products, they do not lend themselves well to making direct comparisons of model performance at the individual iceberg level.

Most of the comparisons in final and cumulative error at 96 hours were not significant (Figures 4.5, 4.8), which is surprising considering the higher temporal resolution of RIOPS (1-hour) and CECOM (3-hour) compared to GLORYS (24 hours). However, there was a significant difference between both CECOM and RIOPS and GLORYS and RIOPS cumulative distance errors over the 2017-2019 hindcast period. Given that RIOPS was shown to consistently counteract the model's tendency to over-estimate drift, this behaviour was expected. While the results of significance testing provide some insight to the differences in model performance between modelled ocean currents, it is acknowledged that they may not be most suitable approach for assessing which ocean current model is the best performer.

An alternative approach to help identify any trends in NAIS model performance between the different sources of modelled ocean currents is to use a pairwise comparison (Figure 5.3), which is calculated by subtracting the distance error between pairs of NAIS outputs using different ocean models. Figure 5.3 shows that there is considerable distance error variability about the zero line for all combinations of ocean current model comparisons, with errors closer to zero indicating comparable model performance. This also seems to indicate that the modelled iceberg drift is largely ocean current model agnostic, and that there is no ocean current product that is consistently better in this study. However, several more subtle trends in performance can be observed. For example, Figure 5.3a shows more distance error lines are found above the zero line at greater magnitudes, which indicates that GLORYS generally performs better than CECOM. Similarly, in Figure 5.3b, RIOPS performs better than CECOM (except for an outlier described in more detail below). Most notably, when comparing the performance of GLORYS and RIOPS (Figure 5.3c), there is no clear better performer.

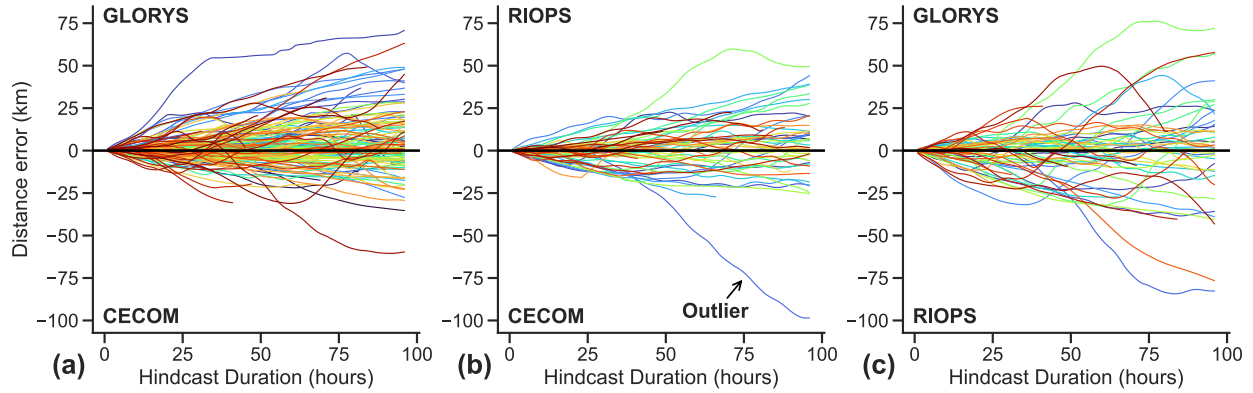


Figure 5.3: Pairwise comparison of distance error for hindcast simulations of iceberg drift using various sources of modelled ocean currents: (a) CECOM vs. GLORYS (2009-2019), (b) CECOM vs. RIOPS (2017-2019), and (c) GLORYS vs. RIOPS (2017-2019). Plot quadrants are annotated with the modelled ocean current that has *improved* distance error performance. Colours indicate individual hindcast simulations.

Using a one-tailed Wilcoxon signed-rank test on each of the paired comparisons of 96-hour final distance error, it was determined that both GLORYS ($p = 0.01$) and RIOPS ($p = 0.04$) were significantly more skilled than CECOM. However, no significant difference was observed between GLORYS and RIOPS ($p = 0.77$). These results are somewhat surprising, as it was assumed that hindcasts run using RIOPS ocean currents, which incorporates tidal currents and heights (Smith et al., 2021), would more accurately predict the drift of icebergs and outperform both the CECOM and GLORYS models, which do not include tides. One possible explanation is that the model has been tuned specifically for use with CECOM modelled ocean currents. Tuning the model for use with RIOPS currents represents an area of future study, as it may result in improvements to overall model skill. Additionally, it is important to stress that the distance error only provides an insight into the absolute distance between observed and modelled iceberg positions and does not take into consideration other performance attributes such as drift direction or speed.

To help better understand the cause of the model behaviour that resulted in the outlier hindcast simulation identified in Figure 5.3b, the underlying driving forces were examined further (Figure 5.4). As the wind and wave forcing data were constant between simulations, the accuracy of this drift simulation appears to be primarily influenced by the speed and direction of the modelled ocean currents. While the CECOM and GLORYS currents flowed generally to the northwest, resulting in acceptable model agreement, the RIOPS ocean currents flowed strongly to the southeast, causing extremely poor model performance. One possible explanation for this

performance may be due to the proximity of Bylot Island, approximately 25 km away. Smith et al. (2021) notes that coastal ocean processes are complex, and that in cases close to the coast, RIOPS may encounter limitations due to the coarse 3-6 km grid used along the Canadian coastline. Thus, the errors associated with the RIOPS ocean current model may, in this instance, explain the poor observed model performance.

Interestingly, the ocean currents in Figure 5.4 also provide insight to the interpolation methods used by the model. As mentioned in Section 5.2.2, the NAIS model interpolates environmental input to hourly timesteps. Both CECOM and GLORYS have 3-hour and 24-hour temporal resolutions, respectively, and must be interpolated, whereas RIOPS has an hourly output and is not interpolated in the NAIS model. Figure 5.4 provides an example of how the use of coarse environmental input data can result in the misrepresentation of short-term processes that can affect drift. For example, semi-diurnal oscillations can be observed in both CECOM and RIOPS modelled ocean currents, however GLORYS ocean currents change only very gradually between timesteps. This again emphasises the importance of using high quality environmental input data, with high temporal resolution.

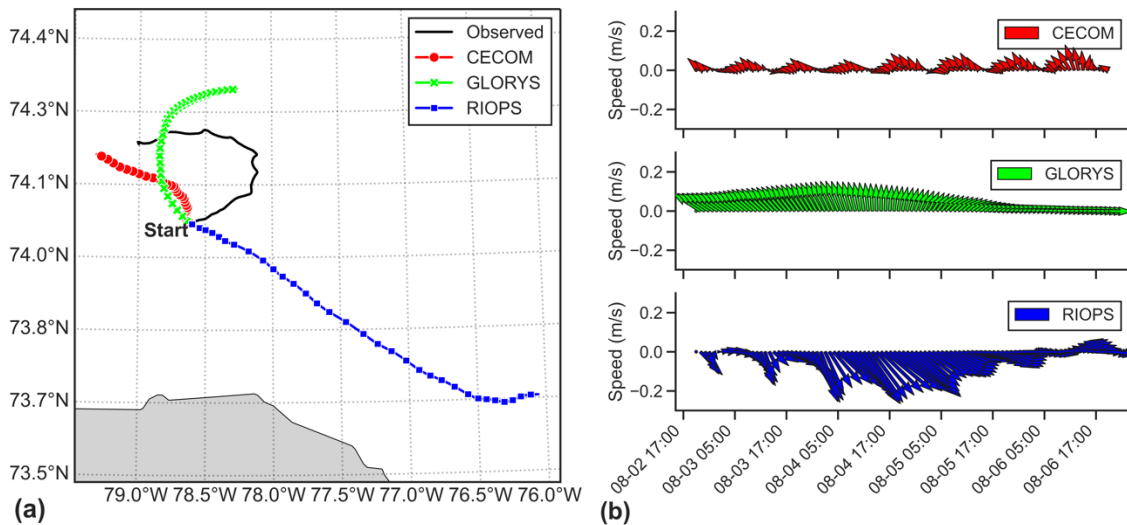


Figure 5.4: (a) Observed iceberg track recorded by beacon 300234060177480 over 96-hours between August 2-6, 2017, and modelled iceberg tracks using CECOM, GLORYS and RIOPS ocean currents. Markers placed every 3 hours. (b) Hourly surface (0-10 m) ocean current velocities acting on the iceberg for each modelled ocean current (Note: CECOM and GLORYS interpolated to hourly timesteps).

5.3 Sensitivity analysis

The sensitivity analysis provides a way to determine the relative importance of the parameters and environmental driving forces on modelled iceberg drift within the study area, and to assess the performance of the NAIS model outside of the region it was initially developed for. The results of the sensitivity analysis were largely consistent with previous studies (Allison et al., 2014; Kubat et al., 2005; Turnbull et al., 2015), with the model most sensitive to ocean current direction, wind direction, iceberg keel geometry and the water drag coefficient. This highlights the importance of good quality wind and ocean currents for both hindcasts and forecasts of iceberg drift. Each of the explored parameters are discussed in further detail below.

5.3.1 *Iceberg waterline length*

Previous sensitivity studies have found the length of an iceberg to have a strong influence on predictions of iceberg drift (Kubat et al., 2005). However, this contrasts with the results of the sensitivity analysis performed in this study, which found the model was largely unaffected by changes in iceberg waterline length (Figure 4.16a). When considering the mean deviation of the final positions to the base case hindcast (Table 4.7), iceberg length was ranked as the second least sensitive parameter. The likely cause of this disagreement is the fact the study by Kubat et al. (2005) employed an empirical relationship with the iceberg's length to estimate cross-sectional area of the sail and keel (Figure 3.10), whereas, in this study, the sail height and keel depth were manually specified, and the number of depth layers were held constant. Changes in iceberg length did, however, modify the above and below-water surface areas of the iceberg and had a considerable influence on calculations of iceberg mass. For example, a 50% reduction in iceberg length resulted in an equivalent 50% reduction in overall surface area, but decreased iceberg mass by 75%. Conversely, a 150% increase in length yielded a 150% increase in surface area but a 225% increase in mass. An example of the changes in the physical characteristics is shown in Table 5.1, where the mass of iceberg C (Table 3.8) varied between 426-3833 kilotonnes depending on the modifier used.

Table 5.1: Example of physical characteristics changed during the sensitivity analysis for Iceberg C located in Davis Strait, Nunavut.

Modifier	Length (m)	Keel Depth (m)	Layers	Sail Area (m ²)	Keel Area (m ²)	Keel Volume (m ³)	Mass (kt)
Waterline length							
50%	72.5	105	11	3045	7345	413,532	426
100%	145.0	105	11	3045	14688	1,654,087	1704
150%	217.5	105	11	3045	22031	3,721,641	3833
Keel depth							
50%	145.0	52.5	6	3045	7345	826,357	851
100%	145.0	105.0	11	3045	14688	1,654,087	1704
150%	145.0	157.5	16	3045	22031	2,483,168	2558

The behaviour of drift trajectories observed in Figure 4.17 can most likely be attributed to the observed changes in iceberg mass and the Coriolis force, which due to influence of the Earth's rotation on a moving object, will cause it to accelerate to the right of its direction of travel in the Northern Hemisphere (Smith, 1993). Gladstone et al. (2001) notes that Coriolis-related forcing is also more significant for larger icebergs, as it is proportional to the mass of the iceberg. Wagner et al. (2017) further explains that since the air and water drag terms scale with surface area, and the Coriolis term scales with volume, the Coriolis term dominates the momentum balance (Eq. 1). This agrees with the drift trajectories observed in Figure 4.17, which illustrate that as the iceberg length (and therefore mass) increases, the drift tracks are deflected to the right and, similarly, when the iceberg length decreases, the drift is deflected to the left. It can also be observed that icebergs E and F, which are the most southerly used in the sensitivity analysis and located off the Labrador Coast, are least impacted by changes in waterline length. This can be explained by the fact that Coriolis-related forcing is stronger at high latitudes. It is suspected that if iceberg keel depth was allowed to vary with iceberg length, results similar to Kubat et al. (2005) would have been observed.

5.3.2 Keel depth

The NAIS model was shown to be considerably more sensitive to changes in keel depth than to changes in iceberg length (Figure 4.16b). While the changes in keel depth did not affect the overall direction or shape of the modelled iceberg drift tracks (Figure 4.18), cumulative

distance travelled by the icebergs varied considerably between perturbation levels. In all cases, decreasing the keel depth resulted in icebergs drifting further than the base case, while increasing the keel depth resulted in icebergs drifting less (Figure 5.5). This behaviour may be attributable to several factors. Mountain (1980) explains that smaller icebergs (i.e., shallower keels) lie mostly in the surface water layer, which can be greatly affected by local wind-driven currents, while larger icebergs (i.e., deeper keels) have much of their cross-sectional area below the influence of local winds. Wind-driven surface currents also give rise to Ekman spirals, which are spirals of moving water 100-150 m deep that run to the right of the surface current in the Northern Hemisphere due to the Coriolis effect (Price et al., 1987). Further examination of the wind and ocean current forces acting on the icebergs modelled in this study revealed that ocean currents were most often strongest in the upper depth layers (i.e., 0-50 m) (e.g., Figure 5.5) and ocean current directions were often in opposition to the prevailing iceberg drift direction at greater depth levels (e.g., 70-140 m). Thus, icebergs with shallower keels that were influenced by fewer depth layers were exposed to stronger near-surface ocean currents, but also less influenced by opposing currents at greater ocean depths. Additionally, since the sail area of an iceberg remained constant in this experiment, the force exerted by the wind represented a greater proportion of the overall forcing experienced by icebergs with shallower keels. Because the iceberg's mass also decreases with lesser keel depth, less force is required to overcome the resisting forces of the iceberg's keel, and therefore wind forces would have a greater influence on iceberg drift. Combined, these factors support the observed pattern of icebergs with shallower keels travelling further, and those with deeper keels travelling less far.

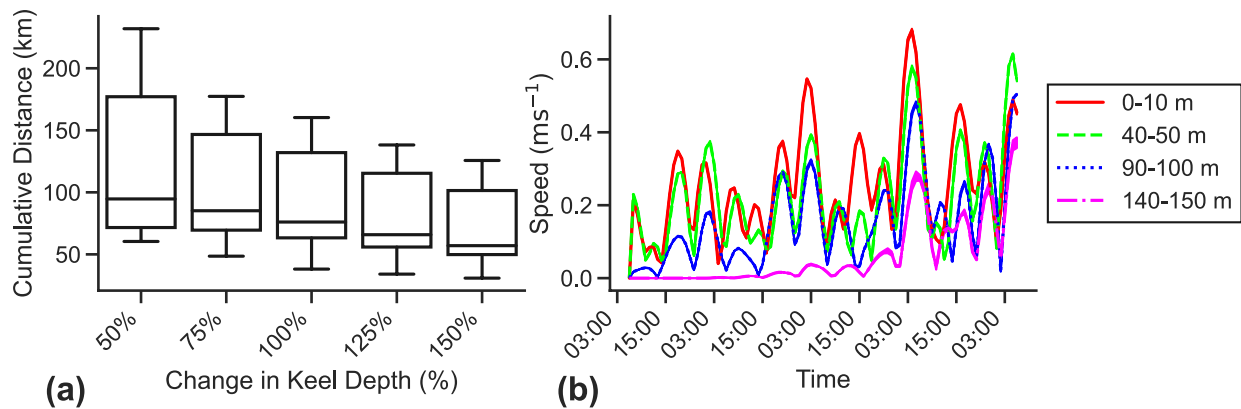


Figure 5.5: (a) Distribution of cumulative distance travelled by icebergs ($n=6$) for each keel depth modifier. (b) Example of the variability of mean RIOPS ocean current speeds at different iceberg keel depth layers for iceberg C, located in Davis Strait.

Iceberg keel geometry represents a major source of uncertainty when modelling the drift of icebergs. Previous studies have attempted to characterize keel cross-sectional areas at different depth intervals from a given waterline length (Barker et al., 2004), but these studies were based on curve-fitting techniques used with a limited observational data set which had few icebergs with keel depths greater than 100 m. Barker et al. (2004) also explicitly state that the empirical equations for describing iceberg keel geometries are not intended for tabular icebergs. This highlights a knowledge gap for characterizing iceberg keel geometries for larger icebergs, such as ice islands, often found in more northerly latitudes and emphasizes the importance of accurately estimating the physical characteristics of an iceberg when collecting *in-situ* measurements. Recent studies (e.g., Schild et al., 2021; Younan et al., 2016) have employed high-quality iceberg profiling systems to acquire detailed information of sail and keel geometries for large icebergs at higher latitudes. A potential area for further study could involve establishing new empirical relationships between the waterline length and keel depths for larger and more complex iceberg shapes, which would in turn benefit future iceberg drift and deterioration modelling studies.

5.3.3 Air drag coefficient

According to Smith (1993), irregularly shaped objects such as icebergs have air drag coefficients (C_a) approximately equal to 1.0. Previous studies have employed a range of C_a values as a tuning parameter between 0.01 to 0.25 to achieve the best fit between predicted and observed iceberg trajectories (Smith & Banke, 1983; Turnbull et al., 2015; Wagner et al., 2017). In this study, model sensitivity to changes in C_a were examined across a range of values between 0.5-2.5, with the results in Figure 4.16c indicating that the model was relatively insensitive to these changes. This is in agreement with Kubat et al. (2005), who found C_a values between 0.5-2.0 to have little effect on forecasts of iceberg drift in the Grand Banks of Newfoundland region. Figure 4.19 illustrates that while the drift direction and shape of the iceberg tracks were not greatly affected, the cumulative distance travelled by the icebergs varied with the air drag coefficient. This behaviour of C_a is expected and can be explained by the model's calculation of the force due to air drag (Eq. 2), as when keeping all other terms constant, the air drag coefficient acts as a multiplier for the total force exerted by the wind on the iceberg sail. Hindcasts using C_a values of 0.5 and 2.5 produced iceberg tracks that were on average 13.7% shorter and 4.5% longer, respectively, than

the base case, which used a default value of 1.9. When using a C_a value of 0.5, the shorter iceberg tracks also resulted in a reduction in overall distance error for all icebergs. This behaviour appears to be counteracting the model's tendency to overestimate drift (Section 4.2.2) by reducing the overall forcing experienced by the iceberg.

At present, the NAIS model's default value for C_a is 1.9, but there is little information regarding the reason for selecting this value. Previous studies have frequently used air and water drag coefficients as fitting parameters, and the values obtained may reflect inadequacies of the overall modelling rather than accurate assessments of the physical drag coefficients themselves. In addition, the model's air drag force calculations do not take into consideration the skin friction drag coefficient of the iceberg. Smith & Banke (1983) note that air form drag is more important for the irregular-shaped icebergs found off the Labrador Coast, but for larger tabular icebergs or ice islands where surface areas greatly exceed the cross-sectional sail area (i.e., 250x larger), the skin friction drag of the iceberg's surface becomes the dominant term. This represents an area of further study for the model when used in more northerly latitudes that are characterized by tabular icebergs with large surface areas.

5.3.4 *Water drag coefficient*

As with the air drag coefficient, previous studies have adjusted the water drag coefficient (C_w) to produce the best possible fit between hindcast and observed iceberg drift tracks (Smith & Banke, 1983). The water drag coefficient is unique to a given iceberg and has been used to account for uncertainties in iceberg surface roughness, keel depth, mass, and variability of current speed with depth (Turnbull et al., 2015). Model sensitivity to perturbations of C_w was assessed using the same 0.5-2.5 range of values as used for C_a in the previous section, which showed that the model was sensitive to changes in C_w . This is in disagreement with Kubat et al. (2005), who found the water drag coefficient to have little effect on drift forecasts and that iceberg velocity closely followed the mean ocean current averaged over the keel depth. The findings of Kubat et al. (2005) are surprising, as the water drag force is considered to be one of the dominant factors affecting iceberg drift, particularly off the Labrador Coast (Smith & Banke, 1983). In a study by Turnbull et al. (2015), the water drag coefficient was found to have a significant impact on modeled drift of icebergs off the west coast of Greenland, with higher values of C_w resulting in greater drift distances. In this study, the opposite was found to be true. Higher values of C_w produced drift

tracks that were consistently shorter compared to the base hindcast, which used a default value of 1.3 (Figure 4.20), and lower values of C_w resulted in longer drift tracks. A value of $C_w = 0.5$ also caused substantially more variability in distance error relative to the base case hindcast simulation, though the reasons for this behaviour is not immediately evident.

Investigation of the model's force calculations revealed that increasing and decreasing the water drag coefficient did not always result in corresponding force magnitudes calculated for each 10 m depth layer. Based on the momentum balance equation (Eq. 3), one would expect that increasing water drag coefficients would cause a greater influence of ocean currents on the modeled iceberg drift and push icebergs further distances. The possibility exists that opposing currents at depth are resisting the prevailing drift direction of the iceberg, although this is unlikely given that the drift behaviour illustrated in Figure 4.20 was consistent amongst all icebergs, which are both spatially and temporally distinct. This may warrant further investigation into the Python code used to calculate the water drag forces, to rule out the possibility of bugs in this version of the model.

5.3.5 *Wind speed & direction*

Previous studies have found winds to be an important factor that can influence iceberg drift (Banke & Smith, 1984; Smith, 1993; Smith & Banke, 1981). This study found the NAIS model to be moderately sensitive to wind speed and extremely sensitive to wind direction. Changes in wind direction (Figure 4.21) produced some of the greatest differences between hindcast simulations of the variables examined in this study, with a mean deviation of 29 km between final modelled positions. As the wind direction was deflected by 30° and 60° to both the left and right of the wind direction provided by the ERA reanalysis dataset, corresponding deflections in drift were observed for all six icebergs. In some cases, the drift distance increased considerably between perturbation levels, but upon closer inspection of the magnitudes of the environmental driving forces, it was found that the direction of the wind and ocean currents were more closely aligned at multiple depths, which accounted for this enhanced drift. This behaviour is in agreement with Crépon et al. (1988), who conducted a detailed study of the response of iceberg drift to changes in wind. It was found that, for lower wind speeds, the drift of an iceberg was more representative of the ocean currents. However, stronger winds were shown to produce higher iceberg velocities and considerable deflections with respect to the prevailing ocean currents.

White et al. (1980) notes that while the influence of wind on iceberg drift is typically small in comparison to the effect of ocean currents, high winds over extended periods of time can have a pronounced effect on resulting iceberg drift trajectories. In this study, changes in wind speed had a considerable effect on the total distance of the modelled drift tracks, which were on average 14% shorter and 16% longer when perturbed by 50% and 150%, respectively. As with the air drag coefficient (Section 5.3.3), the effect of wind speed on modeled iceberg drift is expected due to the calculation of the forces exerted on the iceberg (Eq 2). Figure 4.16f also illustrates that, relative to the base case, distance error tends to decrease at lower wind speeds. Similar to the air drag coefficient case, a reduction in wind-induced drift likely plays a role in counteracting the model's tendency to over-estimate drift (Section 4.2.2) by reducing the total force exerted on the iceberg.

5.3.6 Ocean current speed & direction

Previous studies have found ocean currents to have the most pronounced effect on iceberg drift (e.g., Smith & Banke, 1983; Smith, 1993; Eik et al. 2009; Kechouche et al., 2009; Allison et al., 2014; Zeinali Torbati et al., 2020). These findings are also in agreement with the results of this study, which found the NAIS model to be particularly sensitive to changes in ocean current direction, and somewhat sensitive to ocean current speed (Table 4.7). Changes to ocean current speed had a marked effect on iceberg drift, resulting in drift tracks that were on average 20% shorter and 25% longer when perturbed by 50% and 150%, respectively (Figure 4.23). As with wind speeds, this behaviour is expected when considering the approach used to perturb the ocean currents used in the sensitivity analysis. If the ocean currents at the time and location of the hindcast simulation were weak, there would be little difference between perturbation levels, meaning that the sensitivity of the model may not be accurately captured. Changes in ocean current direction (Figure 4.22) also resulted in considerable variability between hindcast simulations, with a mean deviation of close to 26 km between the final modelled positions. As with wind direction, the deflection of the drift tracks from the base case were also unsurprising, with deflections in drift direction corresponding with the changes in ocean current direction. This emphasizes the need for accurate information about ocean current magnitudes, direction, and variation with depth, as these properties can lead to significant variations in predicted iceberg drift.

5.3.7 *Wind wave height & direction*

Both wind waves and swell waves contribute to the force exerted on an iceberg due to wave radiation stress (Eq 4). Kubat et al. (2005) tested the sensitivity of the NAIS model to wind wave heights between 0.5-2.0 m, and found that heights up to 0.5 m had little effect on iceberg drift, but as wave height increased above 0.5 m the influence on drift became more pronounced. These findings agree with the results of this study, which found the influence of wind waves to be minor when wave heights were small. However, it should be noted that the approach used to assess the model's sensitivity to changes in wind wave heights differed in this study, with wave heights perturbed relative to observed values, as opposed to specifying a constant value as in Kubat et al. (2005). Thus, if the height of the wind waves was zero at the time and location of the hindcast simulation, or wave heights were small, modifying the height of the waves by 50-150% would make little difference. Examination of the observed wind wave heights revealed that this was the case for many of the icebergs used in this study: icebergs A, B, C, and F were exposed to wind waves with heights rarely exceeding 0.5 m, whereas icebergs D and E encountered considerably larger waves with heights between 2.0-6.0 m. This variability in observed wave heights likely accounts for the model's insensitivity to this parameter for specific simulations.

The presence, or lack of, wind waves also likely explained the divergent drift tracks resulting from perturbing the direction of wind waves (Figure 4.24). Smith (1993) explains that wind waves travelling at wind speeds of 10 m s^{-1} will have amplitudes of approximately 1 m. The wave force exerted on the iceberg would be more than double the wind force for an iceberg with average freeboard of 20 m and $C_a = 1.0$. If the waves travel with the wind, the combined force due to waves and wind can be up to three times the wind drag. When considering the direction of the wind waves shown in Figure 4.24, only icebergs D and E were observed to have any noticeable difference in the shape or direction of the drift track. Iceberg D was exposed to smaller wind waves ranging between 0.5-1.0 m, but with a waterline length of 420 m it had a considerably larger sail than iceberg E, which had a length of 134 m but experienced drastically larger waves as high as 5 m for extended periods of time. When the model calculated the wave radiation stresses, the changes in direction of the wind waves served to counteract both the wind and ocean current directions, causing the modelled drift track to diverge from the base case hindcast.

5.3.8 *Swell wave height & direction*

In the NAIS iceberg model, wave forces are calculated separately for wind waves and swell waves but use the same formula (Eq. 4). It is notable that swell waves are not explicitly described in the literature, perhaps since swell waves typically propagate into study areas after having been generated elsewhere, making the collection of environmental data more challenging. When considering the deviation from the base case hindcast, the model was shown to be considerably more sensitive to the height and direction of swell waves compared to wind waves. Much of the explanation described in the previous section can be applied here to explain how the model is influenced by this variable. It should be noted that the methods of ranking the sensitivity of the variables and parameters in Table 4.7 only captures the difference between final position distances and may not encompass the overall importance of the examined variables. In this case, icebergs E and F shown in Figure 4.26 are skewing the rankings. These icebergs were exposed to swell wave heights with a constant magnitude of over 2 m for the duration of the hindcast, whereas the remaining icebergs had swell waves with heights typically below 0.5 m. Due to the distances travelled by icebergs E and F the mean deviation from the final distance error was substantially greater than the other sensitivity analysis results.

It should also be noted when considering the effects of wind and swell waves that iceberg-wave interactions typically have a more pronounced impact on iceberg deterioration than iceberg drift. It is expected the results of the sensitivity analysis would have produced considerably different results if the deterioration functionality in the NAIS model was enabled. As noted in Section 4.3.1, model deterioration was not enabled for hindcast simulations performed in this study and icebergs were assumed to have constant geometry throughout the hindcast period. In a sensitivity analysis by Kubat et al. (2007) it was found that wave action, and most importantly wave height, had the greatest influence on iceberg deterioration, which could account for more than 1 m of melt per day.

Chapter 6: Conclusion

One of the objectives of this study was to determine the suitability of inexpensive, open-source technology for the collection of high spatial and temporal resolution iceberg drift data. This was accomplished through continued development of the Cryologger iceberg tracking beacon, which harnesses low-cost, open-source hardware and software to provide a robust, cost-effective, and user-friendly platform for the collection of long-term iceberg observations. The overall success of the Cryologger deployments has demonstrated to the scientific community that it can provide a reliable method of monitoring iceberg drift patterns within the Canadian Arctic. With a total cost of under \$750 CAD in materials per unit, this represents an economical alternative to existing proprietary commercial systems which can cost 5-10x more. The development and deployment of Cryologgers have enhanced existing iceberg observation networks within Canadian waters and greatly reduced the operational costs of research. The decreased cost per unit has improved the spatial density and coverage of collected data by allowing for a greater number of instrument deployments. The goals of technology developed by this project include lowering the cost of research, encouraging the adoption of open-source technologies for scientific measurements, and enabling innovation in the polar science community. The hope is that researchers will benefit from the accessibility of new instrumentation technologies and end-users will adapt the Cryologger to meet their specific research requirements. New research applications are also constantly being explored for the Cryologger platform, which has already been configured for use as a glacier velocity measurement system, and an automatic weather station in Northern communities.

This study presents the first comprehensive validation of the NAIS iceberg drift model for the Canadian Arctic. A total of 133 hindcast simulations of observed iceberg tracks for the period 2009-2019 were performed using *in-situ* iceberg drift observations of 44 icebergs extracted from the recently compiled iceberg beacon database, including those collected by Cryologger iceberg tracking beacons. The skill of the NAIS model's predictions of iceberg drift was assessed through quantified comparisons of the distance error between observed and modelled drift tracks. Results of the model validation (Section 4.2) demonstrate that the NAIS model produces realistic simulations of iceberg drift for Baffin Bay, as well as for the east coast of Canada. Model results during the initial 24-hour hindcast period had an overall RMSE that fell between 19 and 22 km and increased at a rate of 11-13 km d⁻¹. Results beyond the 48-hour hindcast period are considered

less reliable given the greater variability in RMSE. The majority of hindcasts achieved final distance errors of less than 50 km after 96-hours of simulated drift, which is comparable to current operational forecasts produced by the Canadian Ice Service for the Labrador Coast and Grand Banks of Newfoundland. However, instances of extremely inaccurate (e.g., >150 km) hindcasts were also observed, the cause of which warrants further investigation.

Hindcast simulations displayed similar trends in model performance for Baffin Bay and the Labrador Coast, with both regions exhibiting comparable variability in RMSE throughout both 2009-2019 and 2017-2019 hindcast periods. This suggests that the NAIS model is suitable for use in locations north of 60°N, which are beyond the current area of operational use. Model performance improved when simulating longer (i.e., >250 m) and deeper-keeled (i.e., >100 m) icebergs, irrespective of location. This behaviour is assumed to be due to iceberg interactions with surface ocean currents and local wind effects, which strongly influence the driving forces acting on the above- and below-water portions of the iceberg. Longer, deeper-keeled icebergs counteract the model's tendency to overestimate drift by reducing the overall forcing experienced by the iceberg, thereby reducing overall distance error. This underscores the importance of properly constraining the physical characteristics of icebergs when conducting drift modelling studies.

GLORYS and RIOPS outperformed CECOM in comparisons of the three sources of modelled ocean currents. Model performance is comparable between the three ocean current models during the initial 48 hours of the hindcast period. Beyond the 48-hour point, RIOPS achieves better performance and produces hindcasts with overall lower RMSE values. All ocean current models exhibited similar spatial trends of performance and were observed to encounter more difficulty accurately hindcasting drift in coastal areas and areas with highly variable currents, such as those in northern Baffin Bay. All sources of modelled ocean currents over-estimated iceberg drift for the majority of hindcast simulations, which is attributed to how the NAIS model interpolates environmental input data to higher temporal resolutions to determine the driving forces acting on the icebergs. Notably, RIOPS was found to over-estimate drift less frequently, likely due to its improved hourly temporal resolution and the incorporation of tides, which are better able to represent the short-term variability of observed iceberg drift. Determining how accurately iceberg drift speeds are simulated by iceberg drift modelling studies that employ RIOPS ocean currents represents an exciting topic for further study, as it is anticipated that significant improvements over CECOM and GLORYS will be achieved.

Ocean current direction, wind direction, iceberg keel geometry and the water drag coefficient are the model parameters and environmental driving forces identified by the sensitivity analysis (Section 5.3) as having the greatest influence on modelled iceberg drift. This emphasizes the need for accurate information of ocean current and wind velocities, as these driving forces can lead to significant variations in predicted iceberg drift. Changes in keel depth did not influence the overall direction or shape of the modelled iceberg drift tracks, however, the distance travelled by icebergs with shallower keels was considerably greater than those with deeper keels. This is attributed to the influence of stronger near-surface ocean currents and absence of opposing ocean currents at lower depth levels and highlights the significance of keel depth on predicted iceberg drift. As the water drag force is one of the dominant factors affecting iceberg drift, it is not unexpected that the model would be sensitive to changes in the water drag coefficient. However, unusual model behaviour was observed as this parameter was varied, which does not correspond with the momentum balance equation that governs the NAIS model. Therefore, this parameter should be investigated further to ensure the model is performing as intended.

Future efforts to validate the NAIS model would benefit from additional hindcast simulations of observed iceberg tracks with greater spatial and temporal coverage to address the data gaps identified within Baffin Bay and Davis Strait (Section 5.2.1). The use of high-resolution satellite imagery would also allow for changes in iceberg size to be quantified over time so the model could be run with more accurate inputs of the iceberg's physical characteristics. Given the sensitivity of the model to the iceberg keel depth (Section 5.3.2), the development of novel approaches for estimating the geometries of larger tabular icebergs characteristic of Baffin Bay is warranted. Current empirical relationships based on iceberg waterline length are inadequate for icebergs outside of the NAIS model's current operational area on the east coast of Canada.

This study represents the first comprehensive validation of the NAIS iceberg drift model for the Canadian Arctic and is also the first application of historical *in-situ* iceberg drift observations spanning more over a decade. Considerable time was dedicated to development of the model's Python code, including code modernization to make it easier and more efficient to use, additional functionality to allow the model to operate with a wide range of new environmental forcing data, and enabling the model to run in a hindcast mode. The results of this study will contribute to ongoing efforts by the CIS and NRC to further enhance the NAIS iceberg drift model to forecast the drift path of icebergs more accurately. Iceberg observation data have provided key

insights into the processes that govern iceberg drift and improved our understanding of changing iceberg distributions. When combined with existing data sources, such as satellite imagery, a more holistic understanding of the behaviour of Arctic icebergs can be achieved. Additionally, collected iceberg trajectory data have been shared with the wider IICWG community, with the aim of improving the quality of iceberg forecasts and ensuring safe and efficient marine operations within Canadian waters and beyond.

References

- Allison, K., Crocker, G., Tran, H., & Carrieres, T. (2014). An ensemble forecast model of iceberg drift. *Cold Regions Science and Technology*, 108, 1–9. <https://doi.org/10.1016/j.coldregions.2014.08.007>
- Andersson, L. E., Imsland, L., & Scibilia, F. (2016). An iceberg drift prediction study offshore Newfoundland. *Arctic Technology Conference*. Offshore Technology Conference. <https://doi.org/10.4043/27472-ms>
- Andersson, L. E., Scibilia, F., Copland, L., Aftab, M. F., & Imsland, L. (2018). Analysis of iceberg drift trajectories using the multivariate empirical mode decomposition. *International Society of Offshore and Polar Engineers, ISOPE-I-18-528*, 8.
- Andersson, L. E., Scibilia, F., Copland, L., & Imsland, L. (2018). Comparison of statistical iceberg forecast models. *Cold Regions Science and Technology*, 155, 69–89. <https://doi.org/10.1016/j.coldregions.2018.07.003>
- Andersson, L. E., Scibilia, F., & Imsland, L. (2017). A study on an iceberg drift trajectory. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, 8. <https://doi.org/10.1115/OMAE2017-62159>
- Ballicater Consulting Ltd. (2013). *Ice island and iceberg studies 2013*. (Report 13–01), Canadian Ice Service, Environment and Climate Change Canada. (27 pp.).
- Banke, E., & Smith, S. D. (1984). *A hindcast study of iceberg drift on the Labrador coast* (Canadian Technical Report of Hydrography and Ocean Sciences No. 49). Atlantic Oceanographic Laboratory Ocean Science and Surveys, Atlantic Dept.
- Barker, A., Sayed, M., & Carrieres, T. (2004). Determination of iceberg draft, mass and cross-sectional areas. *Proceedings of the International Offshore and Polar Engineering Conference*, 2, 899–904.
- Beddows, P. A., & Mallon, E. K. (2018). Cave pearl data Logger: A flexible Arduino-based logging platform for long-term monitoring in harsh environments. *Sensors*, 18(2), 530. <https://doi.org/10.3390/s18020530>
- Bigg, G. R., Cropper, T. E., O'Neill, C. K., Arnold, A. K., Fleming, A. H., Marsh, R., Ivchenko, V., Fournier, N., Osborne, M., & Stephens, R. (2018). A model for assessing iceberg hazard. *Natural Hazards*, 92(2), 1113–1136. <https://doi.org/10.1007/s11069-018-3243-x>

- Bigg, G. R., Wadley, M. R., Stevens, D. P., & Johnson, J. A. (1997). Modelling the dynamics and thermodynamics of icebergs. *Cold Regions Science and Technology*, 26(2), 113–135. [https://doi.org/10.1016/S0165-232X\(97\)00012-8](https://doi.org/10.1016/S0165-232X(97)00012-8)
- Bokulich, A., & Oreskes, N. (2017). Models in Geosciences. In L. Magnani & T. Bertolotti (Eds.), *Springer Handbook of Model-Based Science* (pp. 891–911). Springer International Publishing. https://doi.org/10.1007/978-3-319-30526-4_41
- Brown, W. P. and Kerut, E. G. (1978). Air droppable RAMS (ADRAMS) buoys. *Arctic Ice Dynamics Joint Experiment (AIDJEX) Bulletin*, 40, 21–29.
- Canadian Ice Service. (2005). *MANICE: Manual of standard procedures for observing and reporting ice conditions* (Ninth Edition). Canadian Ice Service, Environment Canada. <https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html>
- Carlson, D. F., Boone, W., Meire, L., Abermann, J., & Rysgaard, S. (2017). Bergy bit and melt water trajectories in Godthåbsfjord (SW Greenland) observed by the expendable ice tracker. *Frontiers in Marine Science*, 4(276), Article AUG. <https://doi.org/10.3389/fmars.2017.00276>
- Carlson, D. F., Pavalko, W. J., Petersen, D., Olsen, M., & Hass, A. E. (2020). Maker buoy variants for water level monitoring and tracking drifting objects in remote areas of Greenland. *Sensors*, 20(5), 1254. <https://doi.org/10.3390/s20051254>
- Carrieres, T. (2000). Operational ice-model verification at the Canadian Ice Service. *Annals of Glaciology*, 31, 333–338. <https://doi.org/10.3189/172756400781819824>
- Carrieres, T., Sayed, M. A., Savage, S., & Crocker, G. (2001). Preliminary verification of an operational iceberg drift model. *Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions*.
- Cheema, P. S., & Ahuja, H. N. (1978). Drift of icebergs in the Grand Banks. *Ocean Engineering*, 5(2), 95–103. [https://doi.org/10.1016/0029-8018\(78\)90063-X](https://doi.org/10.1016/0029-8018(78)90063-X)
- Clark, P., Funk, M., Funk, B., Funk, T., Meadows, R. E., Brown, A. M., Li, L., Massey, R. J., & Netterfield, C. B. (2019). An open source toolkit for the tracking, termination and recovery of high altitude balloon flights and payloads. *Journal of Instrumentation*, 14(04). <https://doi.org/10.1088/1748-0221/14/04/P04003>

- Crawford, A. J. (2013). *Ice island deterioration in the Canadian Arctic: Rates, patterns and model evaluation* [Thesis, Carleton University]. <https://curve.carleton.ca/5454680c-2fbc-4e62-b14b-d21d4d42c2bd>
- Crawford, A., Mueller, D. R., Humphreys, E., Carrieres, T., & Tran, H. (2015). Surface ablation model evaluation on a drifting ice island in the Canadian Arctic. *Cold Regions Science and Technology*, 110, 170–182. <https://doi.org/10.1016/j.coldregions.2014.11.011>
- Crépon, M., Houssais, M. N., & Guily, B. S. (1988). The drift of icebergs under wind action. *Journal of Geophysical Research*, 93(C4), 3608. <https://doi.org/10.1029/JC093iC04p03608>
- Crocker, G., English, J., McKenna, R., & Gagnon, R. (2004). Evaluation of bergy bit populations on the Grand Banks. *Cold Regions Science and Technology*, 38(2–3), 239–250. <https://doi.org/10.1016/j.coldregions.2003.12.001>
- Cyr, F., Snook, S., Bishop, C., Galbraith, P. S., Pye, B., Chen, N., & Han, G. (2021). *Physical oceanographic conditions on the Newfoundland and Labrador Shelf during 2019* (No. 2021/017). Fisheries and Oceans Canada. <http://www.dfo-mpo.gc.ca/csas-sccs/>
- Dalton, A., Copland, L., Tivy, A., Van Wychen, W., & Cook, A. (2019). Iceberg production and characteristics around the Prince of Wales Icefield, Ellesmere Island, 1997-2015. *Arctic, Antarctic, and Alpine Research*, 51(1), 412–427. <https://doi.org/10.1080/15230430.2019.1634442>
- De Margerie, S. (1986). *An Operational iceberg trajectory forecasting model for the Grand Banks of Newfoundland*. Environmental Studies Revolving Funds.
- De Veaux, R. D., Velleman, P. F., Bock, D. E., Vukov, A. M., & Wong, A. C. M. (2018). *Stats: Data and Models, Third Canadian Edition*. Pearson Education Canada.
- Diemand, D. (2001). Icebergs. In J. H. Steele (Ed.), *Encyclopedia of Ocean Sciences* (pp. 1255–1264). Academic Press. <https://doi.org/10.1006/rwos.2001.0002>
- Dunn, O. J. (1964). Multiple Comparisons Using Rank Sums. *Technometrics*, 6(3), 241–252. <https://doi.org/10.1080/00401706.1964.10490181>
- Eik, K. (2009). Iceberg drift modelling and validation of applied metocean hindcast data. *Cold Regions Science and Technology*, 57(2–3), 67–90. <https://doi.org/10.1016/j.coldregions.2009.02.009>

- El-Tahan, M., Venkatesh, S., & El-Tahan, H. (1987). Validation and quantitative assessment of the deterioration mechanisms of Arctic icebergs. *Journal of Offshore Mechanics and Arctic Engineering*, 109, 102–108.
- Environment and Climate Change Canada (ECCC). (2019a) Icebergs. <https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/educational-resources/icebergs.html>
- Environment and Climate Change Canada (ECCC). (2019b) Latest ice conditions. <https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions.html>
- Fuglem, M., & Jordaan, I. (2017). Risk analysis and hazards of ice islands. In L. Copland & D. Mueller (Eds.), *Arctic Ice Shelves and Ice Islands* (pp. 395–415). Springer. 10.1007/978-94-024-1101-0_15
- Garrett, C. (1985). Statistical prediction of iceberg trajectories. *Cold Regions Science and Technology*, 11(3), 255–266.
- Garrett, C., Middleton, J., Majess, F., & Hazen, M. (1985). *Analysis and Prediction of Iceberg Trajectories* (p. 131). Department of Oceanography, Dalhousie University.
- Gaskill, H. S., & Rochester, J. (1984). A new technique for iceberg drift prediction. *Cold Regions Science and Technology*, 8(3), 223–234.
- Gladstone, R. M., Bigg, G. R., & Nicholls, K. W. (2001). Iceberg trajectory modeling and meltwater injection in the Southern Ocean. *Journal of Geophysical Research: Oceans*, 106(C9), 19903–19915. <https://doi.org/10.1029/2000jc000347>
- Harris, R., & Jarvis, C. (2011). *Statistics for Geography and Environmental Science*. Routledge. <https://doi.org/10.4324/9781315847610>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ... Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hotzel, I. S., & Miller, J. D. (1983). Icebergs: Their physical dimensions and the presentation and application of measured data. *Annals of Glaciology*, 4, 116–123. <https://doi.org/10.3189/s0260305500005334>

- International Ice Patrol (IIP). (2011). Report of the International Ice Patrol in the North Atlantic (2019 Season Bulletin No. 97 CG-188-66). Retrieved from: https://www.navcen.uscg.gov/pdf/iip/2011_IIP_Annual_Report.pdf
- International Ice Patrol (IIP). (2013). Report of the International Ice Patrol in the North Atlantic (2019 Season Bulletin No. 99 CG-188-69). Retrieved from: https://www.navcen.uscg.gov/pdf/iip/2013_IIP_Annual_Report.pdf
- International Ice Patrol (IIP). (2018). Report of the International Ice Patrol in the North Atlantic (2018 Season Bulletin No. 104 CG-188-73). Retrieved from: https://www.navcen.uscg.gov/pdf/iip/2018_Annual_Report_FINAL.pdf
- International Ice Patrol (IIP). (2019). Report of the International Ice Patrol in the North Atlantic (2019 Season Bulletin No. 106 CG-188-74). Retrieved from: https://www.navcen.uscg.gov/pdf/iip/2019_Annual_Report_FINAL.pdf
- International Ice Patrol (IIP). (2020). Report of the International Ice Patrol in the North Atlantic (2020 Season Bulletin No. 105 CG-188-75). Retrieved from: https://www.navcen.uscg.gov/pdf/iip/Annual_Report_2020.pdf
- Jean-Michel, L., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., Clément, B., Mathieu, H., Olivier, L. G., Charly, R., Tony, C., Charles-Emmanuel, T., Florent, G., Giovanni, R., Mounir, B., Yann, D., & Pierre-Yves, L. T. (2021). The Copernicus global 1/12° oceanic and sea ice GLORYS12 reanalysis. *Frontiers in Earth Science*, 9, 585. <https://doi.org/10.3389/feart.2021.698876>
- Job, J. G. (1978). Numerical modelling of iceberg towing for water supplies—A case study. *Journal of Glaciology*, 20(84), 533–542. <https://doi.org/10.3189/s002214300002092x>
- Jones, D. H., & Gudmundsson, G. H. (2015). Tracking B-31 iceberg with two aircraft-deployed sensors. *Natural Hazards and Earth System Sciences*, 15(6), 1243–1250. <https://doi.org/10.5194/nhess-15-1243-2015>
- Keghouche, I., Bertino, L., & Lisæter, K. A. (2009). Parameterization of an iceberg drift model in the barents sea. *Journal of Atmospheric and Oceanic Technology*, 26(10), 2216–2227. <https://doi.org/10.1175/2009JTECHO678.1>
- Kubat, I., & Sayed, M. (2006). *Implementation of the Canadian Ice Service local iceberg drift model* (HYD-TR-042; Canadian Hydraulics Centre Technical Report). National Research Council of Canada.

- Kubat, I., Sayed, M., Savage, S. B., & Carrieres, T. (2005). An operational model of iceberg drift. *International Journal of Offshore and Polar Engineering*, 15(2), 125–131.
- Kubat, I., Sayed, M., Savage, S. B., Carrieres, T., & Crocker, G. (2007). An operational iceberg deterioration model. *Proceedings of the International Offshore and Polar Engineering Conference (ISOPE)*, 652–657.
- Lane, K., Power, D., Youden, J., Randell, C., & Flett, D. (2004). Validation of synthetic aperture radar for iceberg detection in sea ice. *International Geoscience and Remote Sensing Symposium (IGARSS)*, 1, 125–128. <https://doi.org/10.1109/IGARSS.2004.1368961>
- Larsen, P.-H., Overgaard Hansen, M., Buus-Hinkler, J., Harnvig Krane, K., & Sønderskov, C. (2015). Field tracking (GPS) of ten icebergs in eastern Baffin Bay, offshore Upernavik, northwest Greenland. *Journal of Glaciology*, 61(227), 421–437. <https://doi.org/10.3189/2015JoG14J216>
- Marko, J. R., Birch, J. R., & Wilson, M. A. (1982). A study of long-term satellite-tracked iceberg drifts in Baffin Bay and Davis Strait. *Arctic*, 35(1), 234–240.
- Marko, J. R., Fissel, D. B., & Miller, J. D. (1988). Iceberg movement prediction off the Canadian East Coast. In *Natural and Man-Made Hazards* (pp. 435–462). Springer Netherlands. https://doi.org/10.1007/978-94-009-1433-9_31
- Marko, J. R., Fissel, D. B., Wadhams, P., Bruchhausen, P. M., & Brown, R. D. (1994). Iceberg severity of eastern North America: Its relationship to sea ice variability and climate change. *Journal of Climate*, 7(9), 1335–1351. [https://doi.org/10.1175/1520-0442\(1994\)007<1335:isoena>2.0.co;2](https://doi.org/10.1175/1520-0442(1994)007<1335:isoena>2.0.co;2)
- McCandless, S. W., & Jackson, C. R. (2004). Chapter 1. Principles of Synthetic Aperture Radar. In C. R. Jackson & J. R. Apel (Eds.), *Synthetic aperture radar marine user's manual* (pp. 1–23). NOAA/NESDIS.
- Mongroo, N., & Li, G. (2010). *Canadian Ice Service Iceberg Modelling: A Comparative Analysis of the International Ice Patrol and Canadian Ice Service Iceberg Models* (Report to the Canadian Ice Service).
- Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., & Wood, M. (2019). Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. *Proceedings of the National Academy of Sciences of the United States of America*, 116(19), 9239–9244. <https://doi.org/10.1073/pnas.1904242116>

- Mountain, D. G. (1980). On predicting iceberg drift. *Cold Regions Science and Technology*, 1(3–4), 273–282. [https://doi.org/10.1016/0165-232X\(80\)90055-5](https://doi.org/10.1016/0165-232X(80)90055-5)
- Mueller, D., Copland, L., & Jeffries, M. O. (2017). Changes in Canadian Arctic ice shelf extent since 1906. In L. Copland & D. Mueller (Eds.), *Arctic Ice Shelves and Ice Islands* (pp. 109–148). Springer. 10.1007/978-94-024-1101-0_5
- Mueller, D. R., Crawford, A., Copland, L., & Van Wychen, W. (2013). *Ice island and iceberg fluxes from Canadian High Arctic sources* (Contract Report Final Report; Issue Final Report, p. 23). Northern Transportation Assessment Initiative, Innovation Policy Branch, Transport Canada.
- Münchow, A., Padman, L., & Fricker, H. A. (2014). Interannual changes of the floating ice shelf of Petermann Gletscher, North Greenland, from 2000 to 2012. *Journal of Glaciology*, 60(221), 489–499. <https://doi.org/10.3189/2014JoG13J135>
- Murphy, D. L., & Carrieres, T. (2010). *CIS-IIP iceberg model inter-comparison* (Report to the North American Ice Service, p. 27).
- Murray, J. E. (1969). The drift, deterioration and distribution of icebergs in the north Atlantic Ocean. In: *The Ice Seminar, Canadian Institute of Mining and Metallurgy Special Volume*, 10, 3–18.
- Olenicoff, S. M., 1973. The Soviet DARMS program: twenty years of development, deployment and data. *Arctic Ice Dynamics Joint Experiment (AIDJEX) Bulletin*, 22, 8–35.
- Peterson, I. K., & Prinsenberg, S. J. (2014). *Drift of sea ice and icebergs on the Labrador Shelf in 2009 and 2011 from satellite-tracked ice beacons* (Canadian Technical Report of Hydrography and Ocean Sciences No. 295; p. 21).
- Peterson, I. K., Prinsenberg, S. J., Pittman, M., & Desjardins, L. (2009). The drift of an exceptionally-large ice island from the Petermann Glacier in 2008. *Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, POAC*, 2, 1047–1056.
- Petrie, B., & Isenor, A. (1985). The near-surface circulation and exchange in the Newfoundland Grand Banks region. *Atmosphere-Ocean*, 23(3), 209–227. <https://doi.org/10.1080/07055900.1985.9649225>

- Planck, C. J., Whitlock, J., Polashenski, C., & Perovich, D. (2019). The evolution of the seasonal ice mass balance buoy. *Cold Regions Science and Technology*, 165, 102792. <https://doi.org/10.1016/j.coldregions.2019.102792>
- Price, J. F., Weller, R. A., & Schudlich, R. R. (1987). Wind-Driven Ocean Currents and Ekman Transport. *Science*, 238(4833), 1534–1538. <https://doi.org/10.1126/science.238.4833.1534>
- Rabault, J., Sutherland, G., Gundersen, O., Jensen, A., Marchenko, A., & Breivik, Ø. (2020). An open source, versatile, affordable waves in ice instrument for scientific measurements in the Polar Regions. *Cold Regions Science and Technology*, 170. <https://doi.org/10.1016/j.coldregions.2019.102955>
- Robe, R. Q., Maier, D. C., & Russell, W. E. (1980). Long-term drift of icebergs in Baffin Bay and the Labrador Sea. *Cold Regions Science and Technology*, 1(3–4), 183–193. [https://doi.org/10.1016/0165-232X\(80\)90047-6](https://doi.org/10.1016/0165-232X(80)90047-6)
- Savage, S. (2001a). *Advances and refinements for CIS iceberg and sea ice modules* (Technical Report No. 2001–1; p. 15). Canadian Ice Service, Environment and Climate Change Canada.
- Savage, S. (2001b). Aspects of iceberg deterioration and drift. In N. J. Balmforth & A. Provenzale (Eds.), *Geomorphological Fluid Mechanics* (pp. 279–318). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-45670-8_12
- Schild, K. M., Sutherland, D. A., Elosegui, P., & Duncan, D. (2021). Measurements of iceberg melt rates using high-resolution GPS and iceberg surface scans. *Geophysical Research Letters*, 48(3), Article 3. <https://doi.org/10.1029/2020GL089765>
- Smith, G. C., Liu, Y., Benkiran, M., Chikhar, K., Colan, D. S., Gauthier, A.-A., Testut, C.-E., Dupont, F., Lei, J., Roy, F., Lemieux, J.-F., & Davidson, F. (2021). The regional ice ocean prediction system v2: A pan-Canadian ocean analysis system using an online tidal harmonic analysis. *Geosci. Model Dev*, 14, 1445–1467. <https://doi.org/10.5194/gmd-14-1445-2021>
- Smith, S. D. (1993). Hindcasting iceberg drift using current profiles and winds. *Cold Regions Science and Technology*, 22(1), 33–45. [https://doi.org/10.1016/0165-232X\(93\)90044-9](https://doi.org/10.1016/0165-232X(93)90044-9)
- Smith, S. D., & Banke, E. G. (1983). The influence of winds, currents and towing forces on the drift of icebergs. *Cold Regions Science and Technology*, 6(3), 241–255. [https://doi.org/10.1016/0165-232X\(83\)90045-9](https://doi.org/10.1016/0165-232X(83)90045-9)

- Smith, S. D., & Banke, E. G. (1981). A numerical model of iceberg drift. *Proceedings of the 6th International Conference on Port and Ocean Engineering under Arctic Conditions*, 2, 1001.
- Smith, S. D., & Donaldson, N. R. (1987). *Dynamic modelling of iceberg drift using current profiles* (Canadian Technical Report of Hydrography and Ocean Sciences No. 91). Fisheries and Oceans, Canada.
- Sudom, D., Lamontagne, P., Sayed, M., & Savage, S. (2014). *Assessment of performance of ice island model and iceberg drift and deterioration model* (Technical Report OCRE-TR-2014-017; p. 44). National Research Council Canada.
- Sulak, D. J., Sutherland, D. A., Enderlin, E. M., Stearns, L. A., & Hamilton, G. S. (2017). Iceberg properties and distributions in three Greenlandic fjords using satellite imagery. *Annals of Glaciology*, 58(74), 92–106. <https://doi.org/10.1017/aog.2017.5>
- Sutherland, D. A., Roth, G. E., Hamilton, G. S., Mernild, S. H., Stearns, L. A., & Straneo, F. (2014). Quantifying flow regimes in a Greenland glacial fjord using iceberg drifters. *Geophysical Research Letters*, 41(23), 8411–8420. <https://doi.org/10.1002/2014GL062256>
- Tang, C. C. L., Ross, C. K., Yao, T., Petrie, B., DeTracey, B. M., & Dunlap, E. (2004). The circulation, water masses and sea-ice of Baffin Bay. *Progress in Oceanography*, 63(4), 183–228. <https://doi.org/10.1016/j.pocean.2004.09.005>
- Tiffin, S., Turnbull, I., Sylvestre, T., & Acevedo, J. (2012). Advances in beacon technology to track drift of sea ice and icebergs. *21st IAHR International Symposium on Ice*, 660–673.
- Turnbull, I. D., Fournier, N., Stolwijk, M., Fosnaes, T., & McGonigal, D. (2015). Operational iceberg drift forecasting in Northwest Greenland. *Cold Regions Science and Technology*, 110, 1–18. <https://doi.org/10.1016/j.coldregions.2014.10.006>
- Valeur, H. H., Hansen, C., Hansen, K. Q., Rasmussen, L., & Thingvad, N. (1996). Weather, sea and ice conditions in eastern Baffin Bay, offshore northwest Greenland: A review. *Mineral Resources Administration for Greenland*, 96–12(December), 37.
- Van Wychen, W., Burgess, D. O., Gray, L., Copland, L., Sharp, M., Dowdeswell, J. A., & Benham, T. J. (2014). Glacier velocities and dynamic ice discharge from the Queen Elizabeth Islands, Nunavut, Canada. *Geophysical Research Letters*, 41(2), 484–490. <https://doi.org/10.1002/2013GL058558>

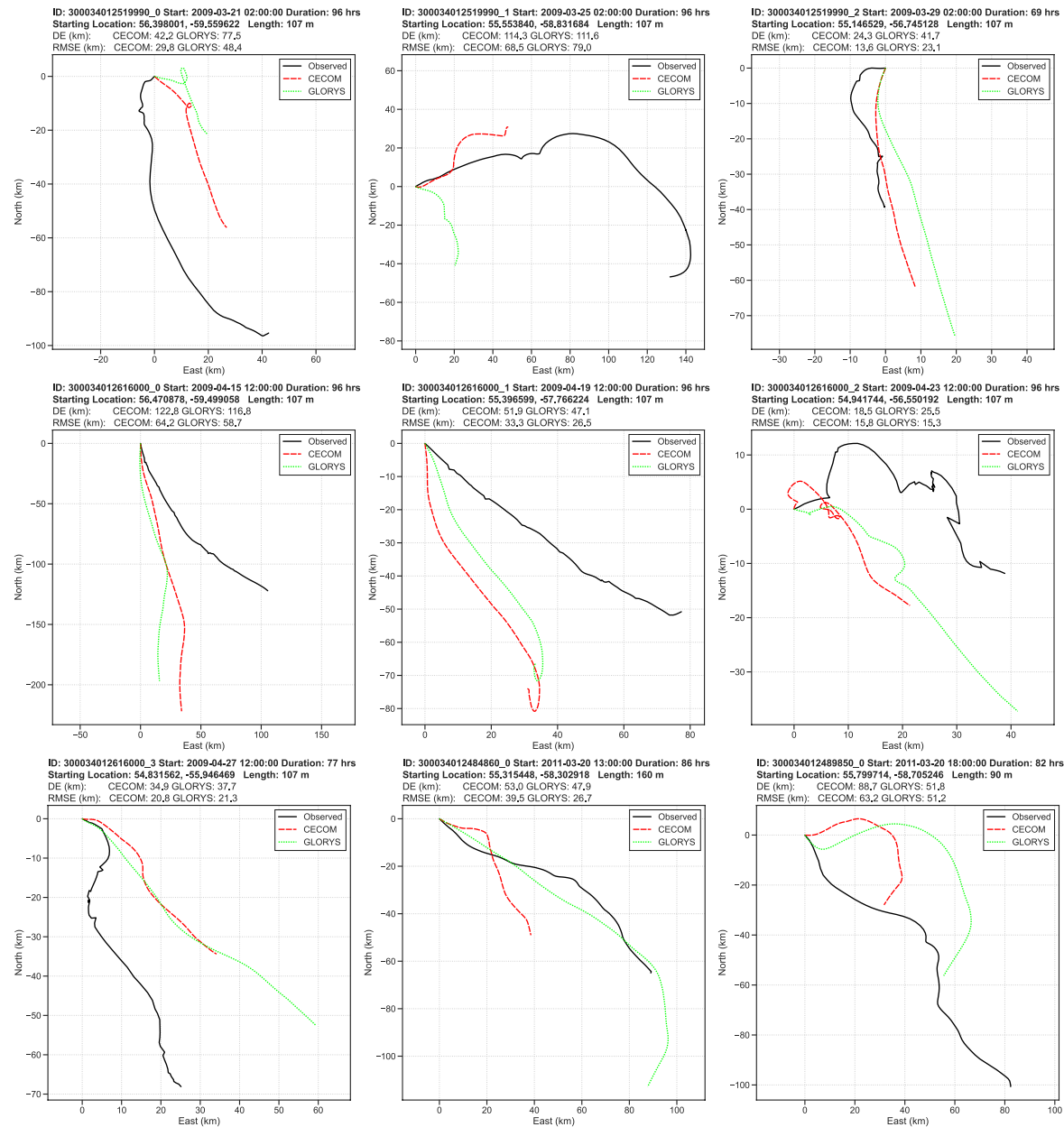
- Van Wychen, W., Copland, L., Gray, L., Burgess, D., Danielson, B., & Sharp, M. (2012). Spatial and temporal variation of ice motion and ice flux from Devon Ice Cap, Nunavut, Canada. *Journal of Glaciology*, 58(210), 657–664. <https://doi.org/10.3189/2012JoG11J164>
- Van Wychen, W., Davis, J., Burgess, D. O., Copland, L., Gray, L., Sharp, M., & Mortimer, C. (2016). Characterizing interannual variability of glacier dynamics and dynamic discharge (1999–2015) for the ice masses of Ellesmere and Axel Heiberg Islands, Nunavut, Canada. *Journal of Geophysical Research F: Earth Surface*, 121(1), 39–63. <https://doi.org/10.1002/2015JF003708>
- Wychen, W. V., Burgess, D., Kochtitzky, W., Nikolic, N., Copland, L., & Gray, L. (2021). RADARSAT-2 derived glacier velocities and dynamic discharge estimates for the Canadian High Arctic: 2015–2020. *Canadian Journal of Remote Sensing*, 46(6), 695–714. <https://doi.org/10.1080/07038992.2020.1859359>
- Wagner, T. J. W., Dell, R. W., & Eisenman, I. (2017). An analytical model of iceberg drift. *Journal of Physical Oceanography*, 47(7), 1605–1616. <https://doi.org/10.1175/JPO-D-16-0262.1>
- Wainwright, J., & Mulligan, M. (Eds.). (2004). *Environmental modelling: Finding simplicity in complexity*. Wiley.
- White, A., & Copland, L. (2019). Loss of floating glacier tongues from the Yelverton Bay region, Ellesmere Island, Canada. *Journal of Glaciology*, 65(251), 376–394. <https://doi.org/10.1017/jog.2019.15>
- White, F. M., Spaulding, M. L., & Gominho, L. (1980). *Theoretical estimates of the various mechanisms involved in iceberg deterioration in the open ocean* (p. 133) [Technical Report]. Office of Research and Development, United States Coast Guard.
- Williamson, S., Sharp, M., Dowdeswell, J., & Benham, T. (2008). Iceberg calving rates from northern Ellesmere Island ice caps, Canadian Arctic, 1999–2003. *Journal of Glaciology*, 54(186), 391–400.
- Willmott, C., & Matsuura, K. (2005). Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate Research*, 30, 79–82. <https://doi.org/10.3354/cr030079>
- Wolford, T. C. (1982). *Sea Ice and Iceberg Conditions, 1970–79* (Northwest Atlantic Fisheries Scientific Council Studies No. 5; pp. 39–42).

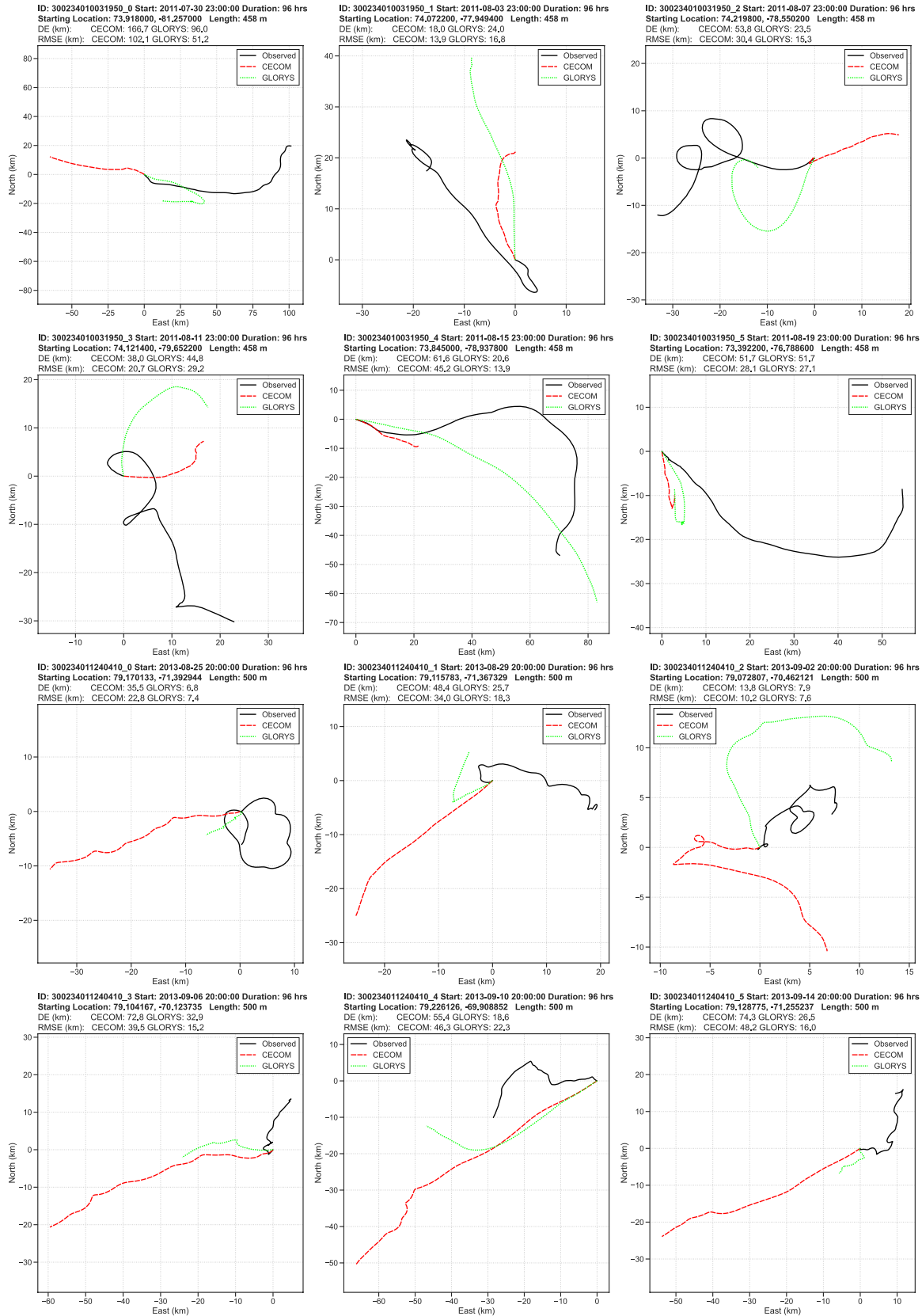
- Wu, Y., Hannah, C. G., Petrie, B., Pettipas, R., Peterson, I., Prinsenberg, S., Lee, C. M., & Moritz, R. (2013). *Ocean current and sea ice statistics for Davis Strait* (No. 284; Canadian Technical Report of Hydrography and Ocean Sciences, p. 55).
- Wyche, W. V., Burgess, D., Kochtitzky, W., Nikolic, N., Copland, L., & Gray, L. (2020). RADARSAT-2 derived glacier velocities and dynamic discharge estimates for the Canadian High Arctic: 2015–2020. *Canadian Journal of Remote Sensing*, 46(6), 695–714. <https://doi.org/10.1080/07038992.2020.1859359>
- Yashayaev, I. (2007). Hydrographic changes in the Labrador Sea, 1960–2005. *Progress in Oceanography*, 73(3), 242–276. <https://doi.org/10.1016/j.pocean.2007.04.015>
- Younan, A., Ralph, F., Ralph, T., & Bruce, J. (2016, October 24). *Overview of the 2012 Iceberg Profiling Program*. Arctic Technology Conference. <https://doi.org/10.4043/27469-MS>

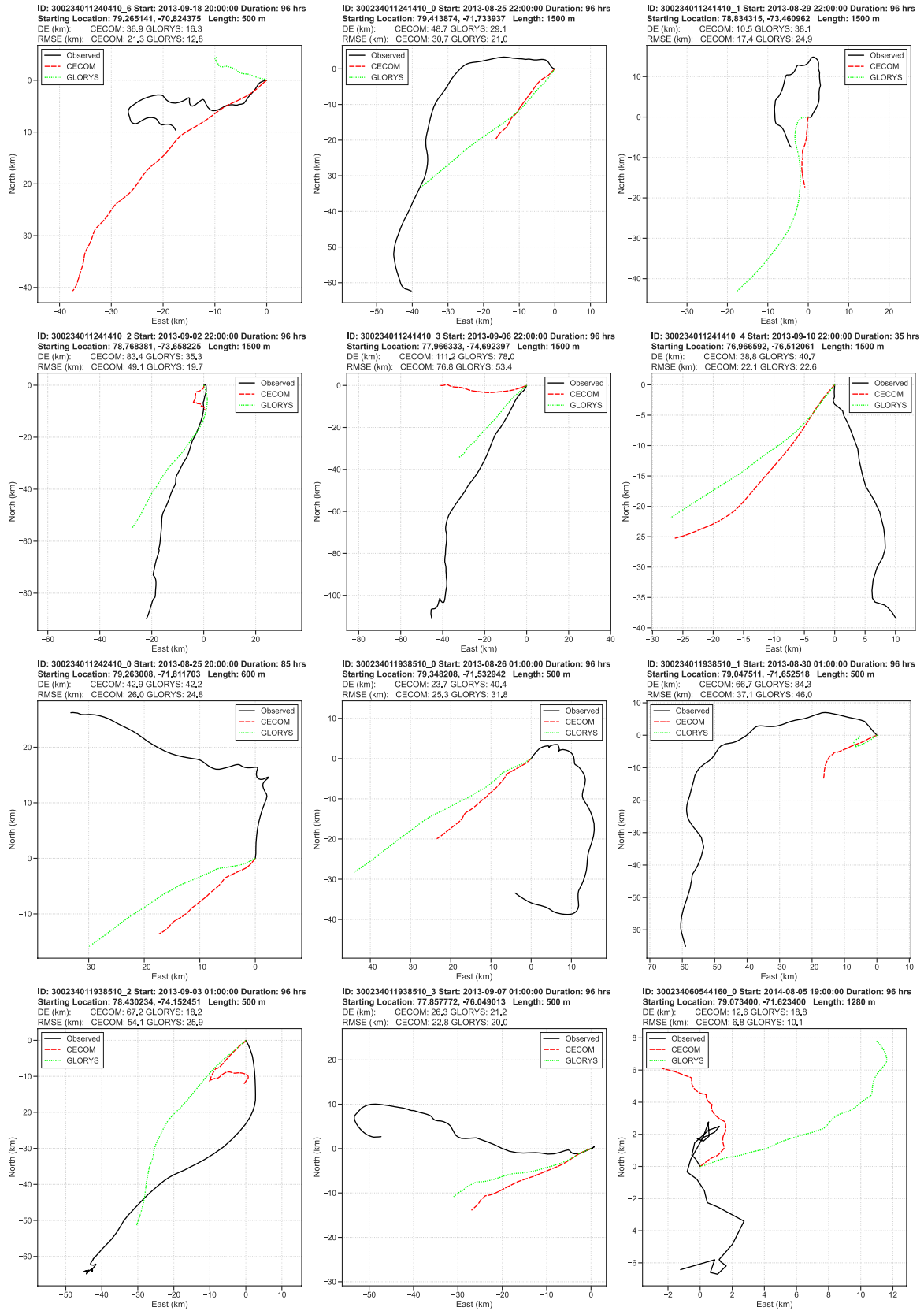
Appendix A: Record of Cryologger deployments made on icebergs in 2018, 2019 and 2021, and estimates of their physical dimensions based on field observations. TAB and PIN shapes refer to tabular and pinnacle icebergs, respectively.

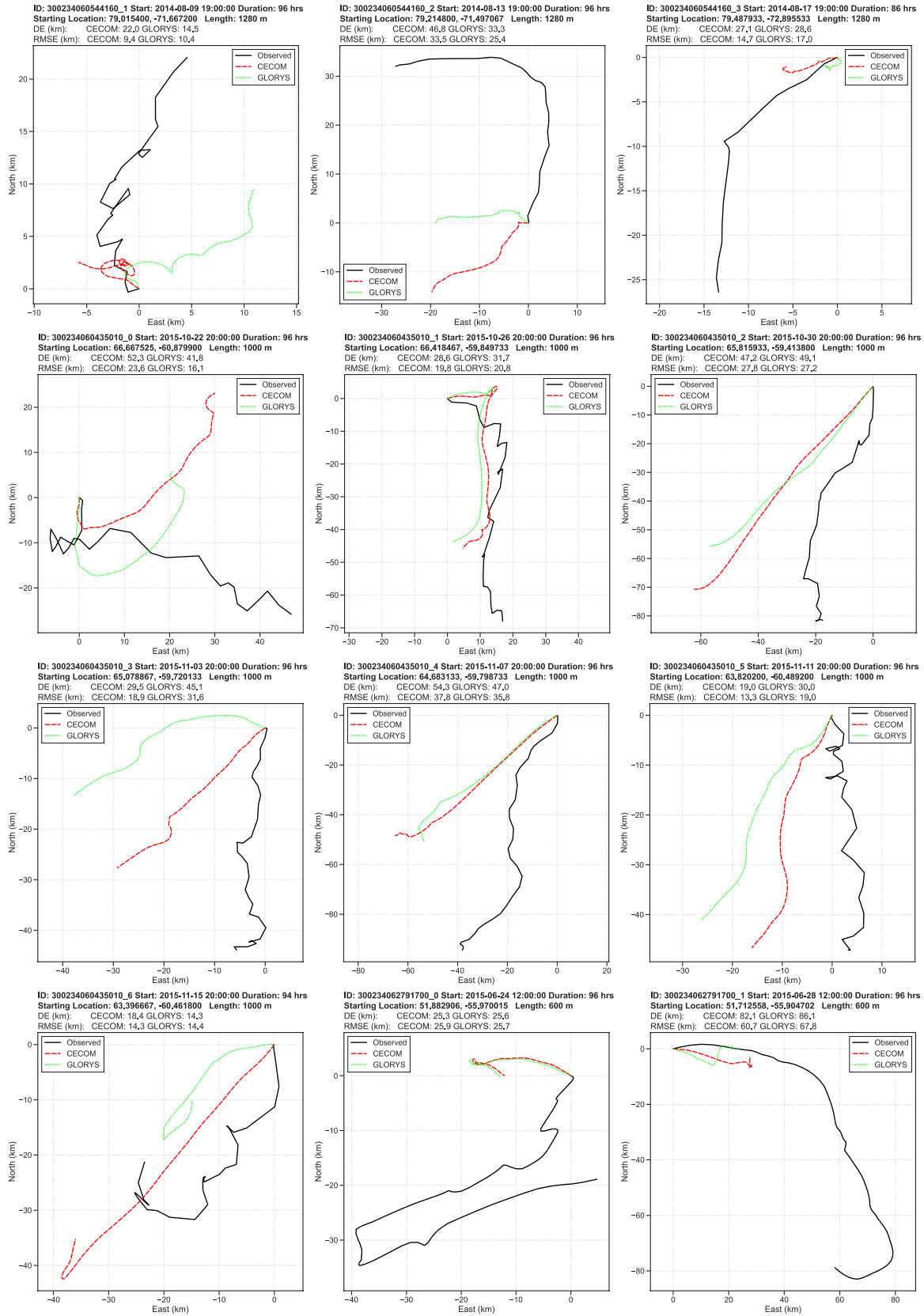
Beacon ID #	Deployment Date (yyyy-mm-dd)	Latitude (°N)	Longitude (°W)	Length (m)	Width (m)	Sail (m)	Shape
300434063418130	2018-09-03	66.218753	-61.986433	370	132	-	TAB
300434063415110	2018-08-27	75.771190	-78.516320	269	204	-	TAB
300434063419120	2018-08-28	77.607430	-76.973940	2650	2500	-	TAB
300434063411050	2018-08-28	77.970320	-78.487720	600	200	-	TAB
300434063415160	2018-09-01	67.357690	-63.270960	2120	1980	-	TAB
300434063416060	2018-09-01	67.538660	-63.364070	400	350	10	TAB
300434063494100	2019-07-30	79.399200	-65.188700	490	300	24	TAB
300434063392070	2019-07-30	79.724500	-65.390300	600	330	18	TAB
300434063394110	2019-08-05	77.972200	-78.414200	760	260	33	TAB
300434063495310	2019-08-05	77.922500	-78.135500	700	240	33	TAB
300434065734810	2021-08-21	67.600430	-61.370630	380	260	72	PIN
300434065732760	2021-08-31	76.564928	-71.793988	250	150	41	TAB
300434065868240	2021-08-21	67.469620	-59.950200	270	160	41	TAB
300434065860260	2021-08-23	67.952950	-61.570470	320	210	55	TAB
300434065869240	2021-08-30	75.432687	-78.743463	310	120	30	TAB
300434065860320	2021-09-01	76.347067	-75.320222	320	280	42	TAB
300434065864290	2021-09-03	77.835600	-76.617500	750	290	25	TAB
300434065861350	2021-09-03	77.494917	-77.032083	250	160	25	TAB
300434063291950	2021-09-03	77.289111	-78.015917	310	300	12	TAB
300434063497310	2021-09-03	77.238833	-78.636028	370	320	9	TAB

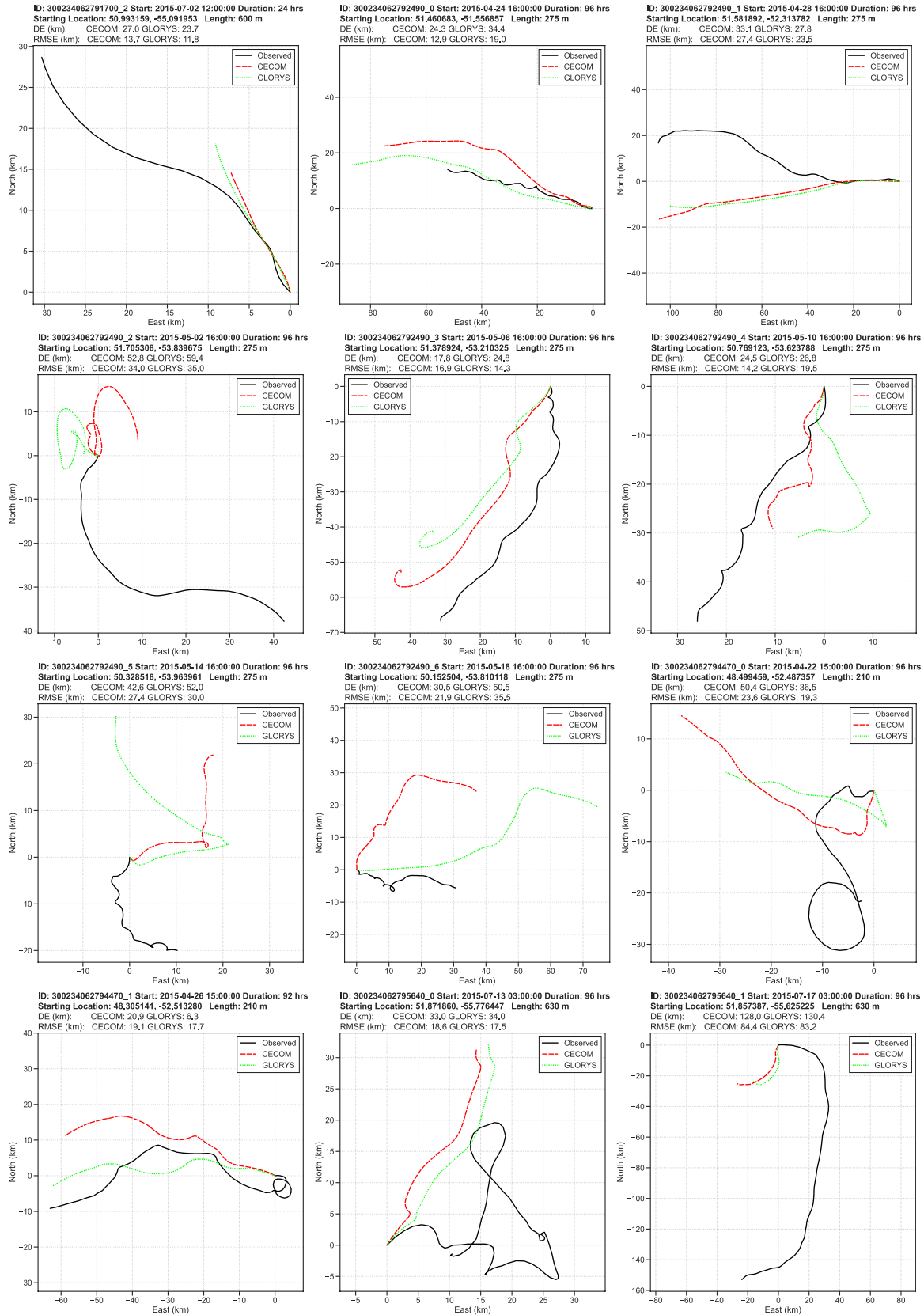
Appendix B: NAIS iceberg drift model validation outputs for the period 2009-2019, including beacon identifier, starting date and position, duration of hindcast, and iceberg length, as well as final distance error (DE) at end of hindcast simulation, and root mean square error (RMSE) of entire iceberg track.



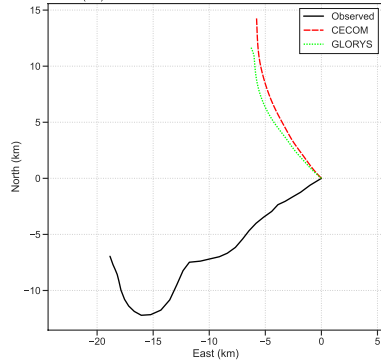




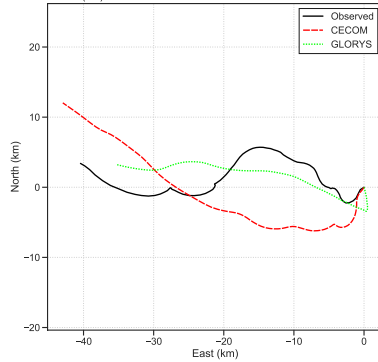




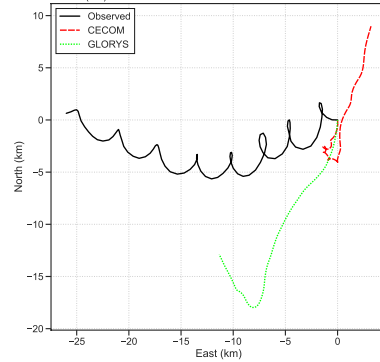
ID: 300234062795640_2 Start: 2015-07-21 03:00:00 Duration: 32 hrs
Starting Location: 50,485624, -56,002180 Length: 630 m
DE (km): CECOM: 24,9 GLORYS: 22,5
RMSE (km): CECOM: 17,4 GLORYS: 16,1



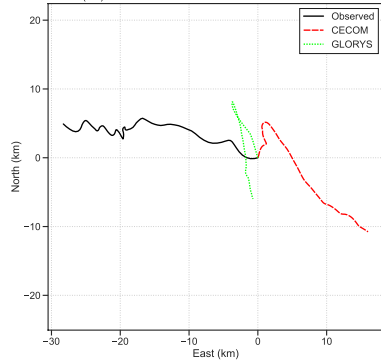
ID: 300234062796490_0 Start: 2015-04-22 20:00:00 Duration: 90 hrs
Starting Location: 48,472701, -52,384884 Length: 100 m
DE (km): CECOM: 9,0 GLORYS: 5,2
RMSE (km): CECOM: 7,8 GLORYS: 9,0



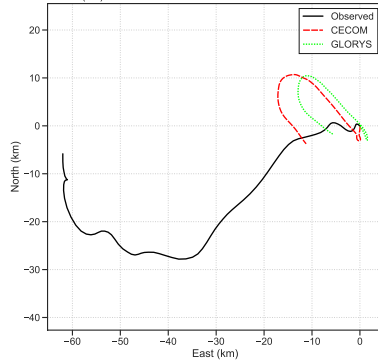
ID: 300234060172440_9 Start: 2016-08-08 01:00:00 Duration: 96 hrs
Starting Location: 76,564300, -71,868890 Length: 175 m
DE (km): CECOM: 30,4 GLORYS: 19,9
RMSE (km): CECOM: 15,8 GLORYS: 13,1



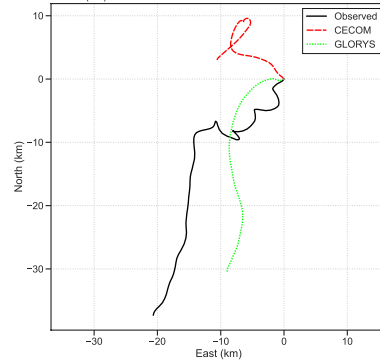
ID: 300234060172440_1 Start: 2016-08-12 01:00:00 Duration: 96 hrs
Starting Location: 76,556670, -72,870700 Length: 175 m
DE (km): CECOM: 47,0 GLORYS: 29,7
RMSE (km): CECOM: 27,5 GLORYS: 17,5



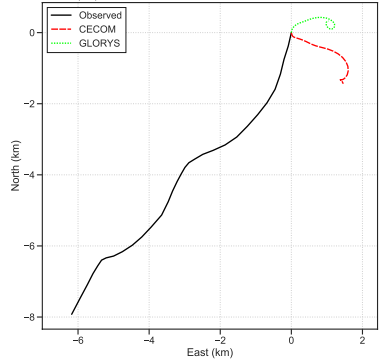
ID: 300234060172440_2 Start: 2016-08-16 01:00:00 Duration: 87 hrs
Starting Location: 76,607470, -73,956800 Length: 175 m
DE (km): CECOM: 50,8 GLORYS: 56,5
RMSE (km): CECOM: 37,1 GLORYS: 39,5



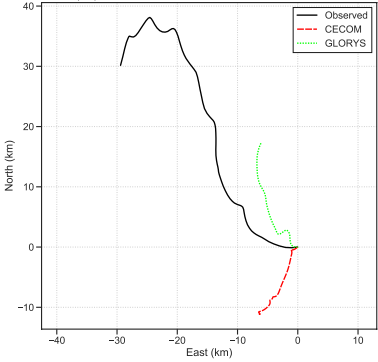
ID: 300234060172670_9 Start: 2016-09-05 01:00:00 Duration: 96 hrs
Starting Location: 70,649090, -67,746530 Length: 1150 m
DE (km): CECOM: 41,8 GLORYS: 13,5
RMSE (km): CECOM: 23,8 GLORYS: 7,1



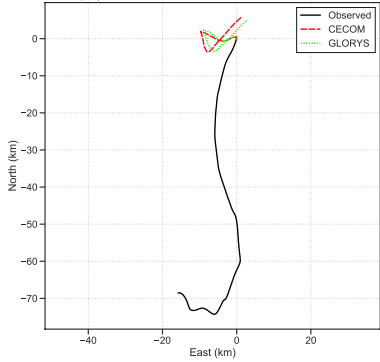
ID: 300234060172670_1 Start: 2016-09-09 01:00:00 Duration: 31 hrs
Starting Location: 70,317410, -68,316560 Length: 1150 m
DE (km): CECOM: 10,0 GLORYS: 11,0
RMSE (km): CECOM: 6,1 GLORYS: 6,7



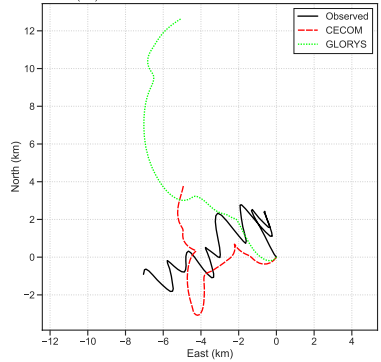
ID: 300234063515450_0 Start: 2016-08-12 18:00:00 Duration: 96 hrs
Starting Location: 76,386800, -76,330600 Length: 420 m
DE (km): CECOM: 47,4 GLORYS: 26,7
RMSE (km): CECOM: 35,5 GLORYS: 21,5



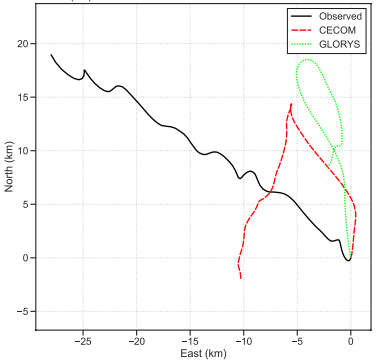
ID: 300234063515450_1 Start: 2016-08-16 18:00:00 Duration: 96 hrs
Starting Location: 76,648400, -77,498000 Length: 420 m
DE (km): CECOM: 76,2 GLORYS: 75,9
RMSE (km): CECOM: 53,3 GLORYS: 53,3



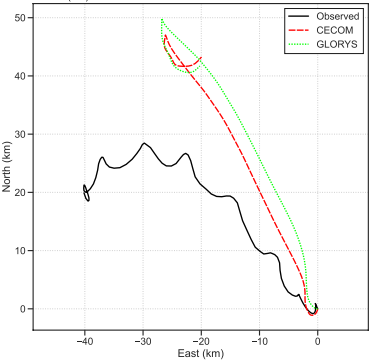
ID: 300434063218800_0 Start: 2016-08-08 01:00:00 Duration: 96 hrs
Starting Location: 76,175140, -69,938680 Length: 350 m
DE (km): CECOM: 5,2 GLORYS: 13,7
RMSE (km): CECOM: 2,6 GLORYS: 7,0

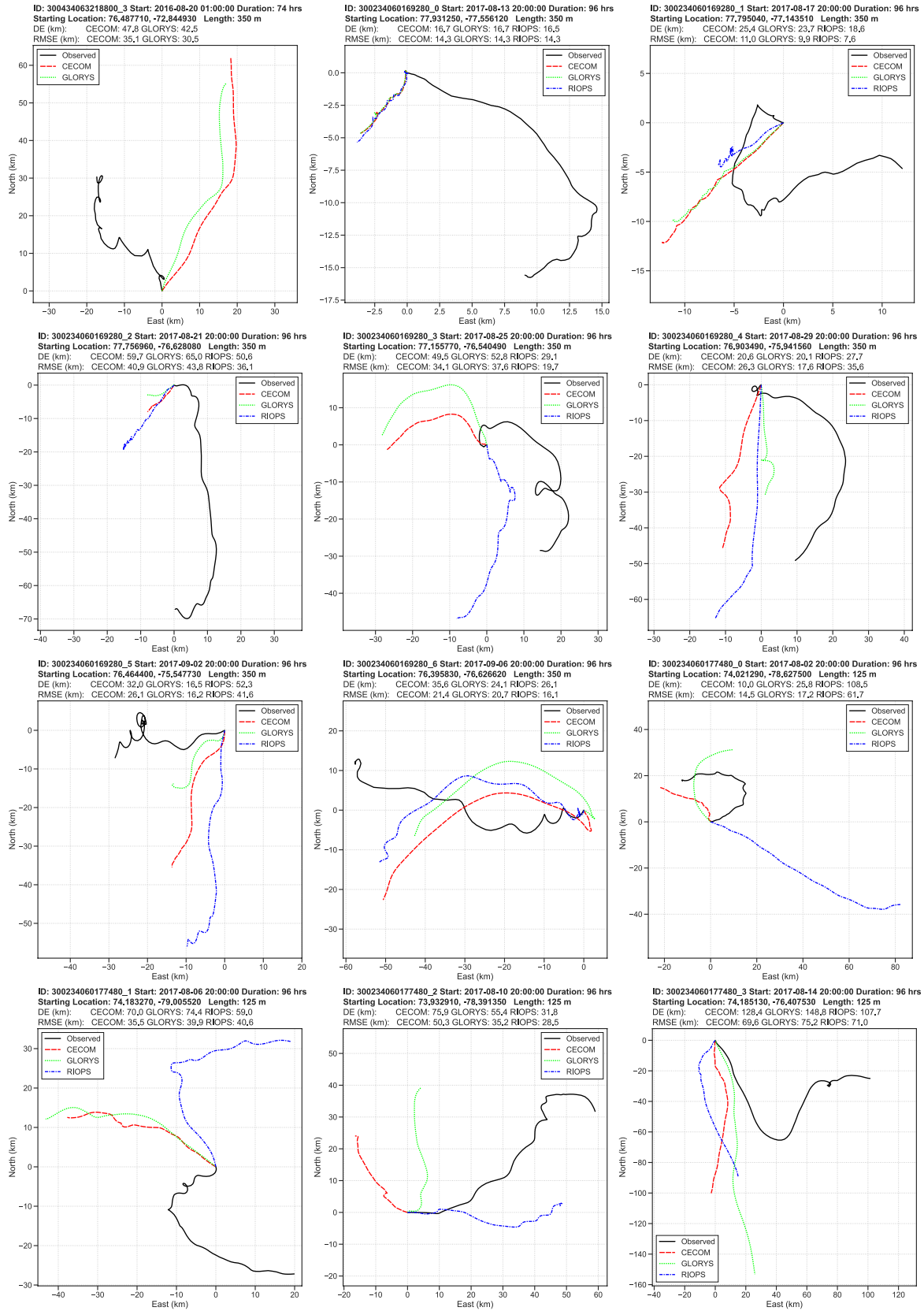


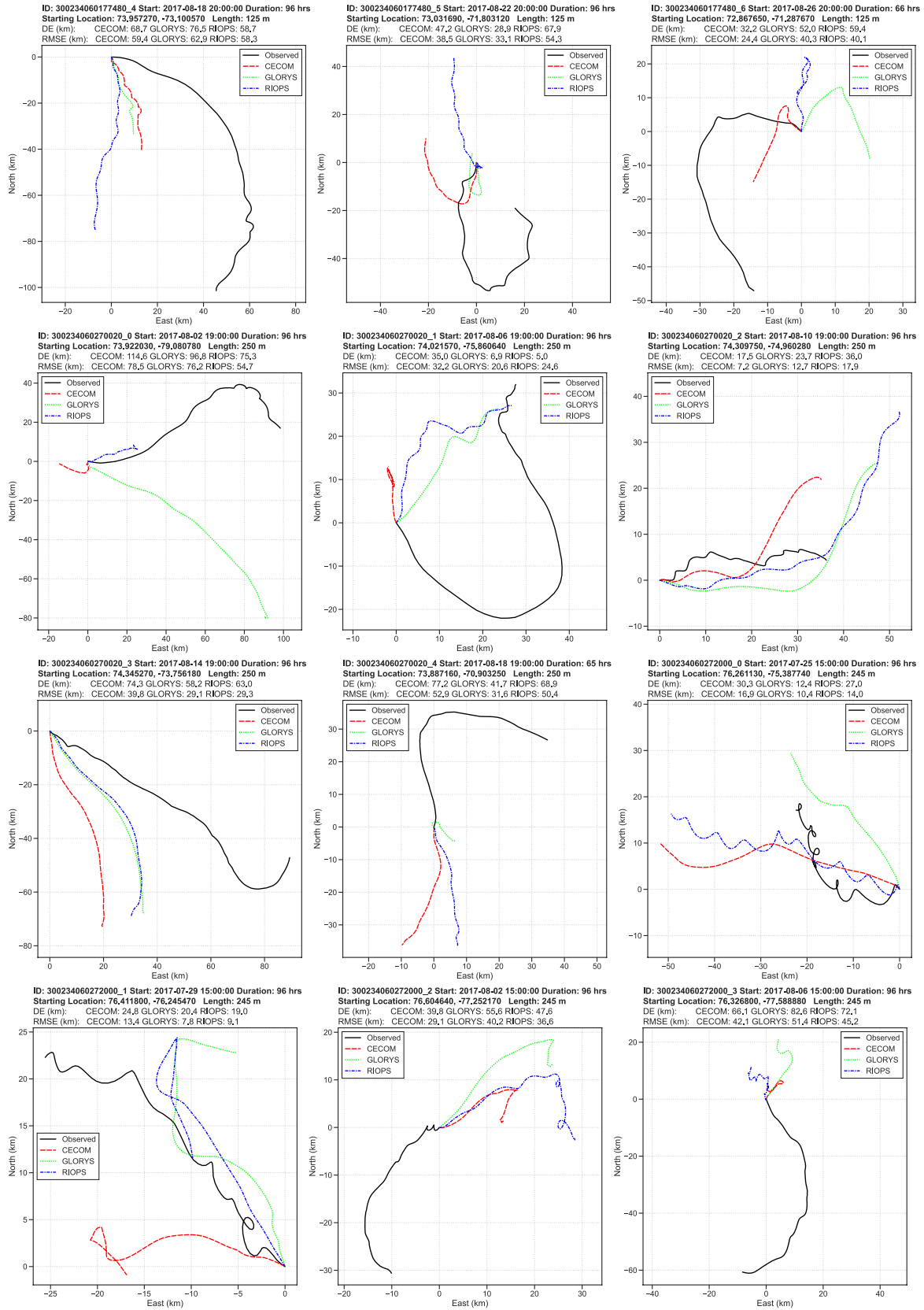
ID: 300434063218800_1 Start: 2016-08-12 01:00:00 Duration: 96 hrs
Starting Location: 76,165842, -70,202138 Length: 350 m
DE (km): CECOM: 27,4 GLORYS: 28,0
RMSE (km): CECOM: 12,6 GLORYS: 15,7

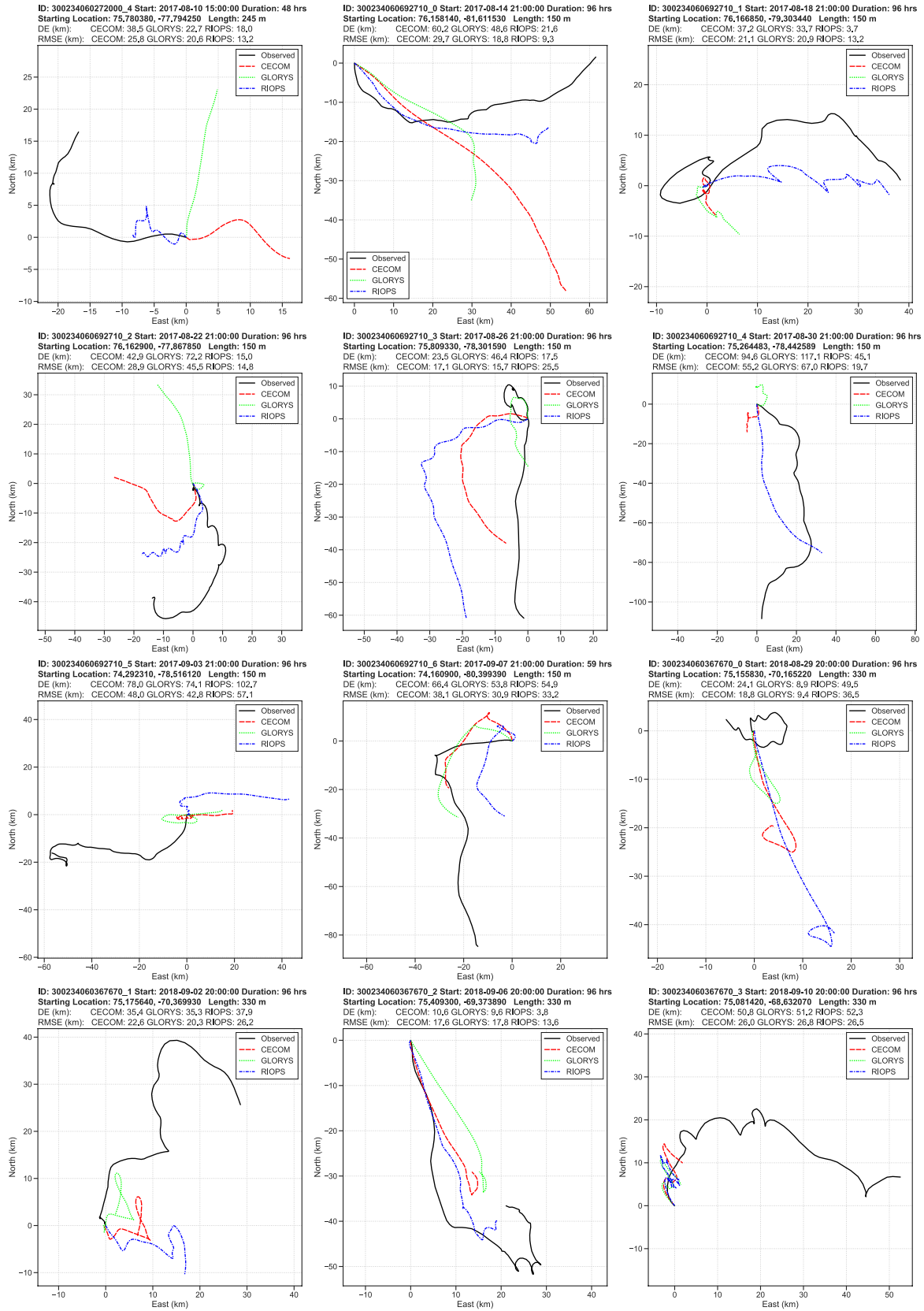


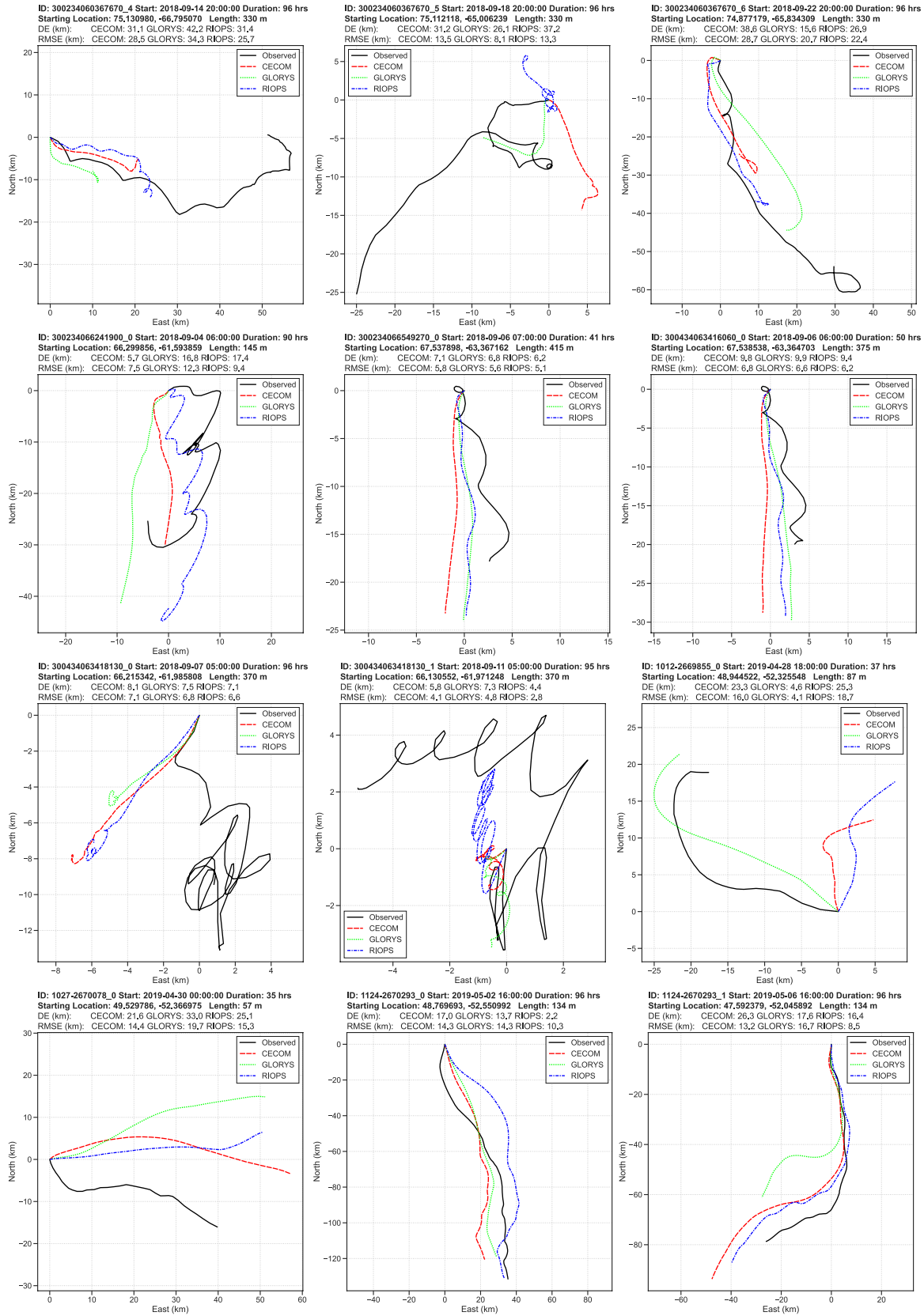
ID: 300434063218800_2 Start: 2016-08-16 01:00:00 Duration: 96 hrs
Starting Location: 76,328340, -71,277540 Length: 350 m
DE (km): CECOM: 30,9 GLORYS: 29,5
RMSE (km): CECOM: 15,8 GLORYS: 17,3

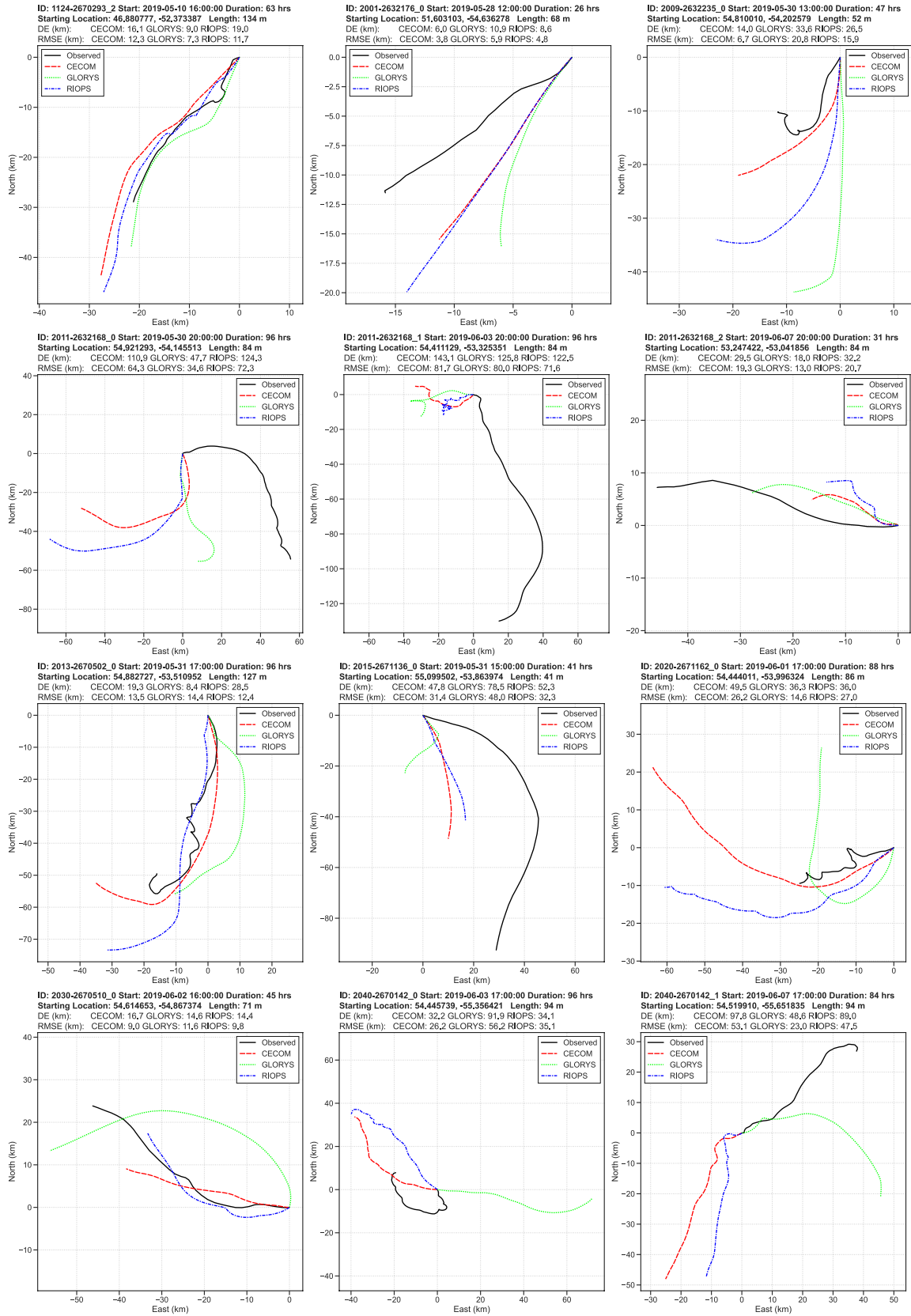




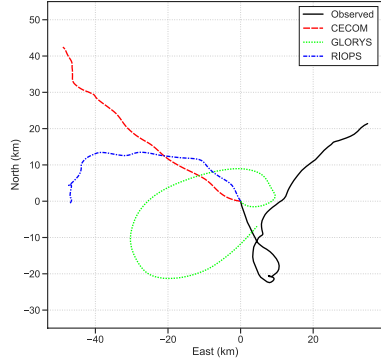




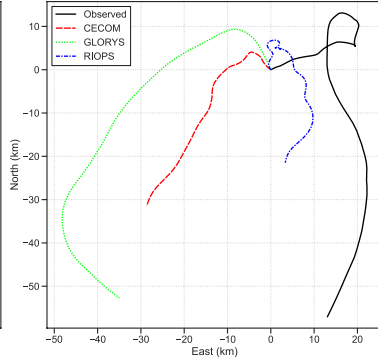




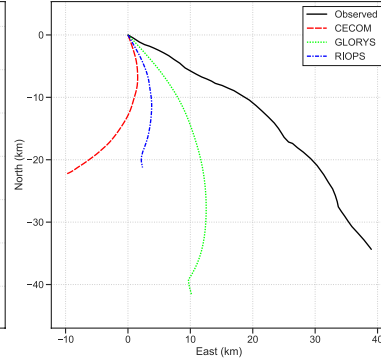
ID: 2045-2670074_0 Start: 2019-06-02 23:00:00 Duration: 96 hrs
 Starting Location: 54,621528, -55,535098 Length: 54 m
 DE (km): CECOM: 86,8 GLORYS: 41,6 RIOPS: 84,8
 RMSE (km): CECOM: 55,8 GLORYS: 34,1 RIOPS: 53,3



ID: 2045-2670074_1 Start: 2019-06-06 23:00:00 Duration: 81 hrs
 Starting Location: 54,805875, -54,983795 Length: 54 m
 DE (km): CECOM: 49,0 GLORYS: 48,2 RIOPS: 36,9
 RMSE (km): CECOM: 31,9 GLORYS: 47,7 RIOPS: 19,5



ID: 3037-2674613_0 Start: 2019-06-29 13:00:00 Duration: 49 hrs
 Starting Location: 54,852152, -54,375666 Length: 61 m
 DE (km): CECOM: 50,3 GLORYS: 29,7 RIOPS: 38,9
 RMSE (km): CECOM: 28,1 GLORYS: 19,5 RIOPS: 22,0



ID: 4013-2674911_0 Start: 2019-07-25 19:00:00 Duration: 71 hrs
 Starting Location: 55,611262, -58,128510 Length: 114 m
 DE (km): CECOM: 55,2 GLORYS: 24,3 RIOPS: 33,0
 RMSE (km): CECOM: 31,1 GLORYS: 18,9 RIOPS: 21,0

