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**ANALYSIS OF ICEBERG DETERIORATION
AND DRIFT USING NAIS 2.0**

by

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ANALYSIS OF ICEBERG DETERIORATION AND DRIFT USING NAIS 2.0

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ABSTRACT

Icebergs present an inherent risk to ship navigation, as collision with an iceberg can have catastrophic consequences. Icebergs are also a crucial source of freshwater flux to the polar oceans, where they can influence ambient water circulation and deep water formation. Prediction of iceberg distribution is thus important for both safe operations in bergy waters and in global climate circulation models. To model the drift of an iceberg, its deterioration—that is, the loss of mass due to thermal (melting) and dynamic (calving) processes—must also be known, since drift rate is dependent upon both the size and shape of the iceberg. In this thesis, we use the state-of-the-art North American Ice Service (NAIS) Iceberg Drift and Deterioration Model v2.0 to identify key deterioration mechanisms and determine major sources of uncertainty. We find the wave erosion parameters have the greatest impact on iceberg prediction, specifically to the form of the iceberg perimeter eroded by wave action. In contrast, the model is insensitive to parameterizations of surface melting. We therefore suggest that future work focus on better resolution and validation of modelled iceberg deterioration.

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LIST OF ACRONYMS AND ABBREVIATIONS

CIS	Canadian Ice Service
CMEMS	Copernicus Marine Environment Monitoring Service
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis fifth generation
GLORYS	Global Ocean Ensemble Physics Reanalysis
IIP	International Ice Patrol
NAIS	North American Ice Service
NRL	Naval Research Laboratory
NSIDC	National Snow and Ice Data Center
USNIC	U.S. National Ice Center

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I. INTRODUCTION

A. MOTIVATION

Icebergs continue to present a hazard to ship navigation and offshore drilling operations. The International Ice Patrol (IIP) in partnership with the Canadian Ice Service (CIS) have identified and tracked icebergs that have become threats to the North Atlantic commercial shipping lanes since 1913. Despite modern detection capabilities, including ship radar, there are still collisions with icebergs. A comprehensive database on all known ship collisions with icebergs (Hill 2005) found 670 collisions, most taking place in the waters around Newfoundland. Iceberg drift is also monitored at operational timescales for risk of collision with offshore drilling platforms and the potential that iceberg scour, or the drag along a shallow bottom, could damage underwater pipelines. Drilling platforms that cannot evade an oncoming iceberg, have “ice management plans” that commonly employ vessels that employ ropes to tow icebergs (Eik 2008). Typically, icebergs are identified using reconnaissance aircraft and, more recently, satellite imagery. However, aerial and satellite reconnaissance cannot always be conducted due to unfavorable flight or reconnaissance conditions. Accurate numerical modeling of iceberg drift then becomes a valuable resource in predicting iceberg locations and the estimated geographic limits of all known icebergs.

To model the drift of an iceberg, its deterioration—the loss of mass due to both thermal (melting) and dynamic (calving) processes—must also be known since the drift rate is dependent upon both the size and the shape of the iceberg (Kubat et al. 2007; Robe 1983; Savage 2001; White et al. 1980). The North American Ice Service (NAIS) Iceberg Drift and Deterioration Model, “NAIS 2.0,” is used for operational prediction of iceberg positions in the Labrador Sea and Grand Banks regions, where the highest incidents of iceberg collisions occur (Hill 2005). It is therefore critical to gain further understanding of the mechanics of iceberg deterioration and their effects on predicted drift to ensure safe navigation in bergy waters. The aim of this thesis is to investigate model uncertainties to improvements deterioration parameterizations.

B. BACKGROUND

The Manual of Standard Operating Procedures for Observing and Reporting Ice Conditions defines an iceberg as “a massive piece of ice of greatly varying shape, protruding 5 meters or more above sea level, which has broken away from a glacier and which may be afloat or aground” (Environment Canada 2005). An iceberg’s size is usually recorded in terms of its length at the waterline, where small icebergs are 15 – 60 m, medium icebergs are 61 – 120 m, large icebergs are 121 – 200 m, and very large icebergs exceed 200 m (Environment Canada 2005). An iceberg’s size and shape evolve throughout its lifespan. Figure 1 shows areas where icebergs are commonly distributed. Besides the regions highlighted, icebergs are also calved from glaciers in eastern Greenland, Svalbard, the Russian Arctic, and Alaska. The most prolific source of Arctic icebergs is the Greenland ice sheet. Icebergs originating from western Greenland, after drifting for one to three years, are those that end up threatening the North Atlantic shipping lanes (IIP n.d.). Figure 2 illustrates the currents that carry icebergs southward to the Grand Banks of Newfoundland. The Grand Banks, an extension of the continental shelf southeast of Newfoundland, is where the cold Labrador current bifurcates to an alongshore and offshore branch. South of the Grand Banks is where icebergs encounter the warm North Atlantic current and quickly deteriorate. IIP’s records of over one hundred years from 1900 to 2000 indicate an average of 479 icebergs per year have entered the shipping lanes (IIP n.d.). IIP uses aerial and satellite reconnaissance to monitor iceberg locations in the NW Atlantic. However, due to adverse weather conditions, such monitoring is not always available.

The inability of various agencies to chart iceberg locations at all times necessitates the use of numerical models. There are two general categories of iceberg models: those that seek to predict the trajectory of individual icebergs on an operational time scale of a week or less and those that seek to model populations of icebergs for their distribution characteristics on seasonal to interannual scales. Operational-scale iceberg models are used by government agencies such as IIP, Canadian Ice Service (CIS), Norwegian Ice Service, and Argentine Ice Service to produce charts marking iceberg locations primarily for the safety of navigation. A challenge that continues to persist in iceberg modeling is the lack of field measurements to validate models, especially for deterioration processes. IIP, CIS,

and other agencies have extensive records charting iceberg locations, but these records don't uniquely identify icebergs and so there is a lack of observations that track the same iceberg over time. Moreover, there are even fewer records that include both an iceberg's position and size.

A great deal of work has been done on developing numerical models to fill these observational gaps. Marko et al. (1993) investigated how future projections of increased iceberg production (due to enhanced glacial melt) would impact iceberg flux to the NW Atlantic. They suggested that the density of icebergs drifted downstream is insensitive to increases in iceberg release rates. They found that although iceberg release rates may increase in future decades, deterioration rates will increase due to the loss of sea ice coverage, which suppresses elevated SST and buffers wave erosion. Bigg et al. (1997) developed one of the first ocean-iceberg coupled numerical models where iceberg melt contributes to ocean forcing, and they applied this model to the North Atlantic. They characterized the importance of various deterioration sources, finding that calving due to wave erosion is a key deterioration mechanism. This model was later applied to assess the risk of iceberg collisions in the SW Atlantic based on possible and probable release scenarios of Antarctic icebergs (Bigg et al. 2018). The released icebergs were simulated to deteriorate and drift using their large-scale iceberg model and were analyzed for the density of icebergs around shipping routes in the Falklands Plateau. The deterioration rate of icebergs is important in this model—and other such models—in assessing iceberg hazards to shipping to determine the number of icebergs that will survive (i.e., not melt) before drifting near shipping routes. In addition, Perez-Gruszkiewicz and Peterson (2018) used an iceberg drift and deterioration model with climate forcing to predict that greater sea surface temperature in the future will result in fewer icebergs surviving the journey from their sources to the NW Atlantic shipping lanes.

Deterioration modeling, in addition to modeling drift, is required to accurately predict the spatial distribution of fresh water introduced to the ocean from icebergs. Resolving oceanic fresh-water fluxes is required to properly represent ambient circulation and deep-water formation. Martin and Adcroft (2010) determined a realistic fresh-water flux from land ice to the ocean to prove that the introduction of icebergs into a coupled

global circulation model enhances deep-water formation. They used statistical distributions of various iceberg sizes determined by the calving flux of parent glaciers, then evaluated the deterioration and drift of these icebergs according to the model of Bigg et al. (1997). Stern et al. (2017) expanded on this work by including large tabular icebergs, more typical of the Antarctic Ocean, in global circulation models to further refine fresh-water flux. However, despite the importance of deterioration, all these models used a simplified deterioration scheme and typically only consider calving, wave erosion, and forced convection. Neshyba and Josberger (1980) and White et al. (1980) developed parameterizations for a greater breadth of deterioration processes, including solar radiation and buoyant vertical convection, which are compiled in Savage (2001). However, the effects of these parameterizations in large-scale iceberg modeling are not well known.

This motivates an investigation into the deterioration mechanisms to determine key uncertainties. We simulate icebergs in various environments, testing a range of key parameters to determine uncertainties in iceberg drift and deterioration. We find that wave erosion parameterization introduces the most uncertainty. In particular, the choice of the perimeter affected by wave action can result in a significant change in melt rate. The outline of this thesis is as follows: Chapter II explains the drift and deterioration model, governing equations, and uncertain parameters that will be tested throughout the study. Chapter III describes the environmental data used and the methodology for the thesis. Chapter IV presents the results of our study, and Chapter V includes our discussion and conclusions, along with suggestions for future work.

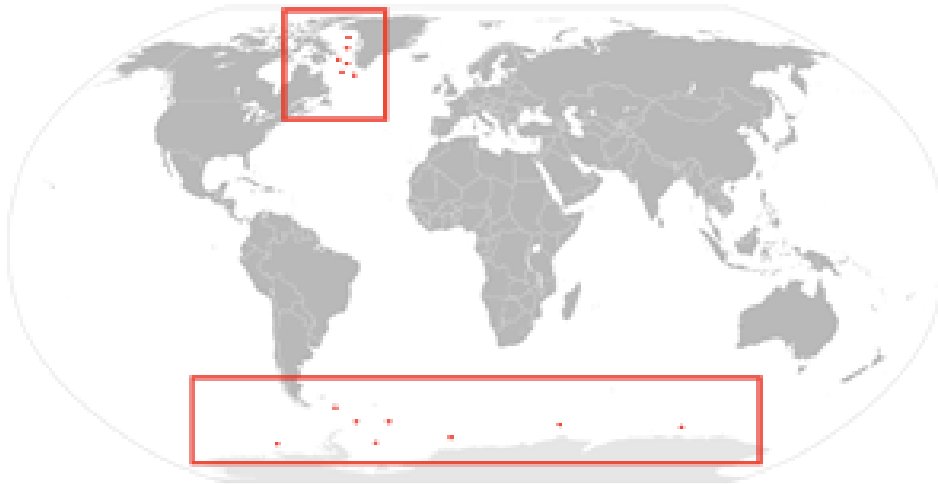


Figure 1. Commonly encountered iceberg locations. Source: NSIDC (n.d.).

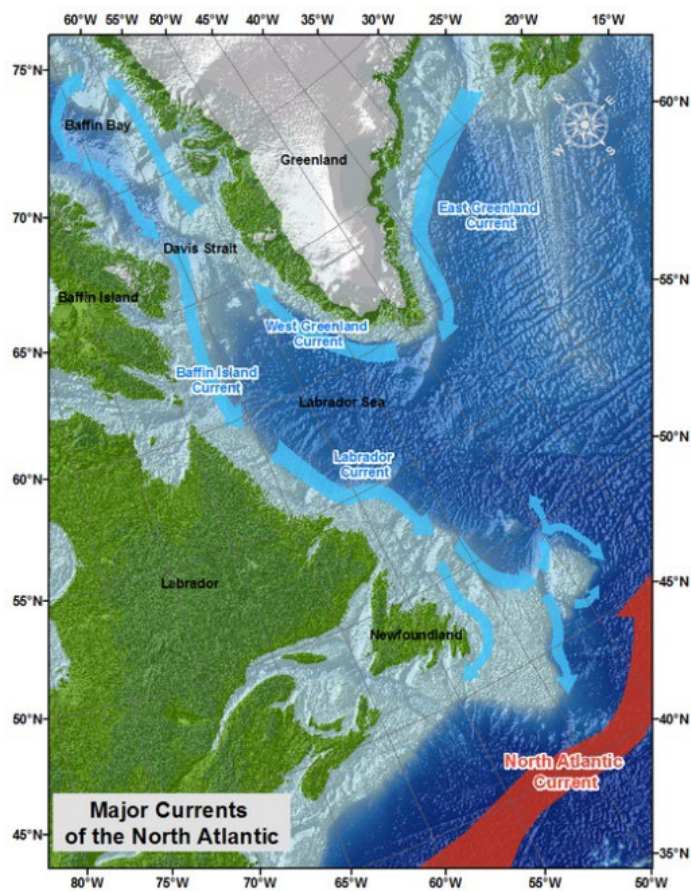


Figure 2. Major currents that influence icebergs in NW Atlantic. Source: IIP (n.d.).

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II. DRIFT AND DETERIORATION MODEL

We simulate the evolution and movement of icebergs in realistic ocean environments using the python version of the NAIS 2.0 model. This model is used by the CIS and IIP for operational iceberg predictions. Figure 3 shows the design flowchart for the model. As shown in Figure 3, the NAIS model independently updates the simulated icebergs according to mechanisms that dynamically drift the icebergs and those that thermodynamically and physically deteriorate the icebergs using a backward Euler method. The code adapts the models for these mechanisms from equations described in Savage (2001). Comprehensive details on the functionality of the model are documented in Tran (2019). For our simulations, icebergs are seeded throughout the model domain at prescribed positions and evolved in time. Advective and deteriorative processes are applied individually to each iceberg. The model is forced by the atmosphere, ocean, and wave data from either manually entered values or reanalysis model data. Metadata of the icebergs are recorded, including position, length, mass, and percent melt.

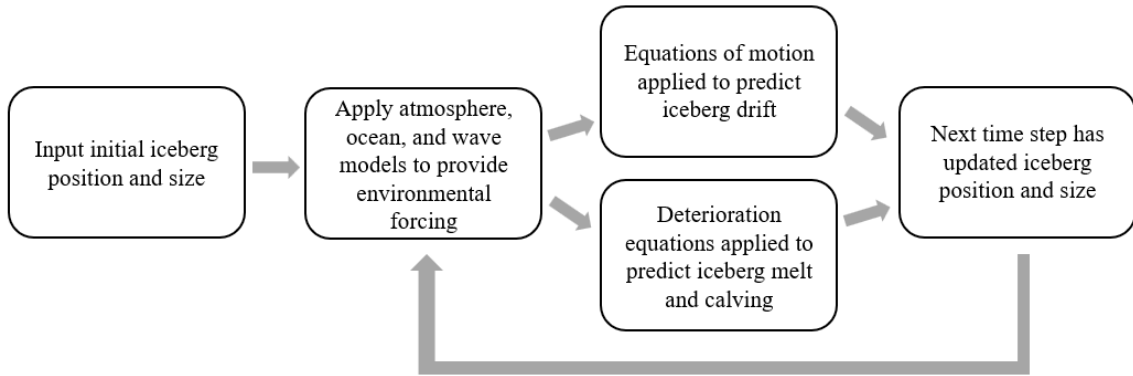


Figure 3. Generalized schematic depicting how an iceberg drift and deterioration model works. Adapted from Savage (2001).

A. GOVERNING EQUATIONS

1. Drift

The governing equation for the drift of an iceberg can be expressed by the following equation of motion (Savage 2001):

$$m\left(\frac{dV}{dt} + \mathbf{f} \times V\right) = \mathbf{F}, \quad (4.1)$$

where m is the iceberg mass, $\mathbf{f}$ is the Coriolis parameter, and V is the velocity of the iceberg. $\mathbf{F}$ is the sum of the following forces: wind drag force, water drag force, the wave radiation stress, pressure gradient force, the force associated with the added mass of the iceberg, and the force due to interactions with sea ice. The acceleration of the body depends directly on the mass and characteristics of an iceberg and therefore a deterioration model must also be included to accurately predict drift.

2. Deterioration

The deterioration of an iceberg is due to numerous processes that result in mass loss. Table 1 lists the deterioration processes and their observed contributions to iceberg deterioration. Figure 4 shows an illustration of the loss mechanisms. Each of these processes is modeled in the NAIS 2.0 code and results in changes to the mass and size of the icebergs. Here, we provide the parameterizations of these processes in NAIS 2.0 in terms of a melt rate, Ψ , which describes the rate at which the waterline length decreases. To go from a loss in the waterline line to total mass loss requires knowledge of the geometry of the iceberg, and the model uses distinct classes to separate these into classes (e.g., tabular, non-tabular). Iceberg deterioration in the model is calculated by

$$\frac{dL}{dt} = -\Psi, \quad (4.2)$$

where L is the waterline length of the iceberg and t is the time in seconds.

Table 1. Contributions of iceberg deterioration mechanisms. Source: Savage (2001)

Deterioration Mechanism	Contribution to total mass loss (%)
Wave erosion	50.6 – 65
Wave induced calving	21.0 - 29.5
Forced convection (water)	11.3 - 24.9
Buoyant vertical convection	1.2 - 1.5
Surface melting	0.3 - 5.3
Forced convection (wind)	0.3 - 2.9

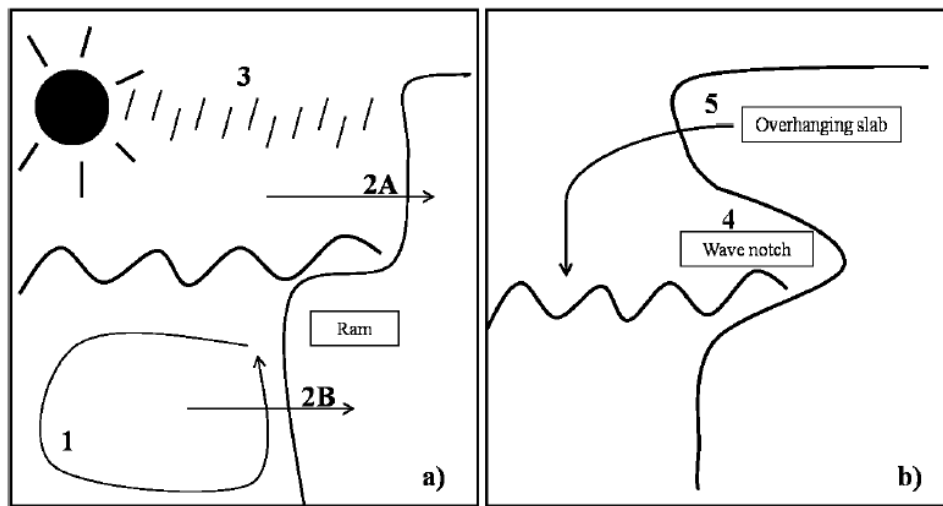


Figure 4. Illustration of iceberg deterioration. 1) buoyant convection, 2A) forced convection, wind, 2B) forced convection, water, 3) surface melting, 4) wave erosion, and 5) calving of overhanging slab. Picture a) shows after an overhanging slab has calved and b) shows before. Source: Crawford (2018)

a. Wave erosion

Wave action at the waterline induces heat transfer from the water to the iceberg surface, causing greater melt than regular convection due to the high orbital velocities of the waves. White et al. (1980) derived the equation for the wave erosion of rough surfaces that, in the context of the iceberg problem, takes the form

$$\psi_{we} = CK^{-1}\Delta TgH\tau P\left(\frac{R}{H}\right)^{0.2} / (1.5L^2), \quad (4.3)$$

where R is the roughness height of the iceberg surface, typically set to 1cm, H is the mean wave height, τ is the mean wave period, and g is the gravitational acceleration. The quantity ΔT represents the temperature difference between the seawater and the melting point of ice, P is the waterline perimeter eroded by waves, which is an ad-hoc function of the waterline length and is given by $3L$ by default, and $1.5L^2$ is an estimate of the typical iceberg surface area. The value C is an empirical coefficient of $5.22 \times 10^{-6} \text{K}^{-1}$.

b. Wave induced calving

As waves erode notches into the waterline of an iceberg, overhanging slabs form, which are then lost through wave-induced calving. White et al. (1980) developed a parameterization for the critical length at which an overhanging slab will calve as

$$F_l = 0.33(37.5mH + 0.196L^2)^{1/2}. \quad (4.4)$$

The associated mass loss due to such a calving event was developed by Savage (2001) as

$$M_c = \rho_i A 0.65(0.196L), \quad (4.5)$$

where A is the plan-view area given as $1.875L0.8F_l$. As calving is an intermittent process, Savage (2001) recommended a periodic calving interval, given as

$$t_c = F_l / \psi_{we} \quad (4.6)$$

The deterioration by calving can then be represented as

$$\psi_c = \frac{1}{3L^3 \rho_i} \frac{M_c}{t_c}. \quad (4.7)$$

c. Forced convection

Icebergs can also lose mass due to forced convection, which is a result of the relative velocity between the iceberg and water producing a temperature difference that leads to convective heat transfer and melting of the keel. The equation for the melting of an iceberg due to forced convection is based on empirical correlations of heat transfer (Savage 2001):

$$\psi_{fw} = \frac{q_f}{\rho_i \Gamma}, \quad (4.8)$$

where ρ_i is the density of ice, $\Gamma=334\text{J/g}$ is the latent heat of fusion, and q_f is the mean heat flux, represented as

$$q_f = \text{Nu} k_f \Delta T / L, \quad (4.9)$$

where k_f is the thermal conductivity. The quantity Nu is the Nusselt number, parameterized by White et al. (1980) as

$$\text{Nu} = 0.056 \text{Re}^{0.8} \text{Pr}^{0.4}, \quad (4.10)$$

where Pr is the Prandtl number of water, the ratio of the kinematic viscosity, ν , to the thermal diffusivity, and Re is the Reynolds number of the iceberg. The Prandtl number is set to be 13.4, the value for seawater at 0°C . We define the Reynolds number, Re, with respect to the waterline length as

$$\text{Re} = v_r L / \nu, \quad (4.11)$$

where v_r is the relative velocity between the iceberg and water. Forced convection in the water is highest when there is a larger relative velocity between the iceberg and current, which occurs when winds are the strongest. When winds are weak, the melting due to forced convection is negligible (Kubat et al. 2007). Forced convection also occurs in the air, melting the sail of the iceberg instead of the keel. The concepts and equations are the same as those for forced convection in water, but they use the relative velocity between the iceberg and the wind field, and the kinematic viscosity of air.

d. Solar radiation

The surface melting of an iceberg due to solar insolation can be approximated as (Savage 2001)

$$V_s = \frac{I}{\Gamma \rho_i} (1 - \alpha), \quad (4.12)$$

where I is the value of the solar insolation and α is the albedo. White et al. (1980) performed theoretical calculations of surface melting rates for a range of insolation values with an albedo of 0.35 and found melting rates ranging from less than 1cm/day up to 7cm/day.

e. Buoyant vertical convection

Melting due to buoyant vertical convection, also known as double-diffusive convection, is a result of a turbulent layer generated close to the iceberg by local salinity and temperature gradients. The melted ice surrounding the iceberg has a much lower salinity than the surrounding seawater, causing it to have positive buoyancy and rise. However, with thermal diffusivity being much larger than the saline diffusivity, the colder and denser ice melt sinks. White et al. (1980) determined that closest to the iceberg, the saline effects of positive vertical buoyancy dominate. Based on laboratory experiments and field observations, Neshyba and Josberger (1980) observed the basal (i.e., underwater) deterioration of an iceberg frozen into the pack ice and thus not subject to wave erosion or forced convection to derive the following empirical relationship for iceberg melting due to buoyant vertical convection

$$V_b = 2.78\Delta T + 0.47\Delta T^2 (\text{m year}^{-1}), \quad (4.13)$$

where ΔT is the difference between water temperature and melting temperature of ice.

3. Model Parameters with Uncertainty

Given the numerous iceberg deterioration mechanisms, the effects of environmental forcing on deterioration are represented by several adjustable parameters. Many of the experiments designed to determine these parameters were based on tank measurements or limited field observations (such as White et al. 1980; Neshyba and Josberger 1980; de Jong 1973). Here we compile background information from previous studies of iceberg deterioration and discuss the uncertainty of the specific parameters listed in Table 2.

Table 2. Model parameters with uncertainty

Parameter	Value used in NAIS 2.0	Tested values
Wave eroded perimeter, P	$3L$	$1.5L$
Roughness height, R	0.01m	0.005m, 0.02m
Wave erosion coefficient, C	$5.22 \times 10^{-6} \text{ K}^{-1}$	$4.698 \times 10^{-6} \text{ K}^{-1}$, $5.742 \times 10^{-6} \text{ K}^{-1}$
Insolation, I	203.5 W/m^2	15 W/m^2 , 350 W/m^2
Albedo, α	0.7	0.5, 0.9

The wave erosion model has several key parameters with known uncertainty. The value P represents the waterline perimeter (as a function of L) that is subject to wave action. Iceberg perimeter as a function of length depends largely on the shape of the iceberg. Field measurements have found that the entire perimeter of an iceberg can be close to $3L$ (El-Tahan et al. 1987; Venkatesh et al. 1985). Given a predominantly single-direction wave field acting upon an iceberg, we posit a lower limit of $\frac{1}{2}$ the total perimeter to be affected by wave erosion. In this case, we believe a value of $3L$ could be an overestimate of the waterline eroded by waves for a given timestep. As such, we reduce the P to 1.5 to determine its influence on deterioration. The iceberg surface roughness height, R , may also take on a range of values. (Kubat et al. 2007; Savage 2001; White et al. 1980). Higher roughness heights can increase the heat transfer from wave action due to forced convection. The typical value for the roughness height of the iceberg surface is estimated at 1 cm (El-Tahan et al. 1987; Kubat et al. 2007; Savage 2001; White et al. 1980). However, some studies have used roughness heights as large as 2 cm (Robe 1983), though this may also underestimate actual values. White et al. (1980) mentioned the strong influence of roughness height and suggested that future field studies are needed to investigate the relationship of roughness height to deterioration and calving. The last parameter we investigate within the wave erosion equation is the empirical coefficient, C . This value is determined through estimates of the Reynolds number and a ratio of the iceberg surface roughness height to the wave height (White et al. 1980). In the absence of uncertainty information on this value, we set to test sensitivity by varying this coefficient by ten percent.

Solar insolation is the total radiation, or solar energy reaching the earth's surface, and is used in Equation 2.12 for surface melting. This quantity varies based on the latitude, time of year, and atmospheric scattering/absorption. The daily mean of insolation values can range from 15W/m^2 in December to a peak of around 203.5W/m^2 in July (de Jong 1973). However, due to persistent cloud cover and fog in the area over those dates, these numbers are reduced by approximately 40%. Thus, an upper limit for the maximum solar insolation for July with no cloud or fog cover would be 350W/m^2 (de Jong 1973). Another parameter that may take on a range of values is the iceberg albedo, used in Equation 2.12 for surface melting. Albedo is the amount of solar radiation reflected by a surface. While many studies have measured the albedo of snow, glaciers, and sea ice, few have directly estimated the albedo of icebergs. One study that measured the albedo of Antarctic icebergs found values up to 0.88 (Warren et al. 2019). In the absence of studies measuring Arctic iceberg albedo and given that icebergs are floating pieces of glacial ice, we looked for studies into the albedo of Greenland glaciers. While Elmes et al. (2021) found an overall mean albedo of 0.79 for the entire Greenland Ice Sheet, one glacier on the west coast of Greenland was measured to have an albedo as low as 0.5. Given that albedo is highest at times when fresh snow is present and lowest in months when meltwater forms, we consider this lower limit of 0.5, as we expect icebergs in our region of study to be experiencing constant melt.

III. DATA AND METHODOLOGY

A. ENVIRONMENTAL FORCING DATA

NAIS 2.0 relies on environmental input data from ocean, atmosphere, and wave models to dynamically drift and thermodynamically deteriorate icebergs, predicting their trajectories. The data required from each input model are listed in Table 3. For deterioration sensitivity tests, we construct a simplified environment with constant wind velocity, air temperature, current velocity, water surface temperature, and wave characteristics. For tests investigating the effect of deterioration parameters on the drift, we apply reanalysis model data. The atmosphere and wave reanalysis data used are from ERA5, the fifth generation ECMWF reanalysis of the global climate. The ERA5 data has hourly estimates of the past environment on a $\frac{1}{4}$ -degree resolution for atmosphere and a $\frac{1}{2}$ -degree resolution for waves (Hersbach et al. 2018). Ocean reanalysis data is from the Global Ocean Ensemble Physics Reanalysis (GLORYS). GLORYS provides daily mean ocean values at an eddy-permitting resolution of $\frac{1}{4}$ degrees (CMEMS 2022).

The environmental data in the vicinity of modeled iceberg(s) are interpolated from the ocean, atmosphere, and wave data. The region of interpolation around the iceberg(s) is limited by the distance any iceberg could travel within the forecast period with a velocity of 5km/h (which is larger than the fastest recorded iceberg motions). To limit the numerical costs of such an interpolation, our forecast intervals are limited to 16 days with a maximum of 20 icebergs per run, but multiple runs can be stitched together to extend this to greater times or include more icebergs in a population.

Table 3. Required model data to run NAIS iceberg model

Ocean Model	Atmospheric Model	Wave Model
U Current	U Wind	Swell height
V Current	V Wind	Swell period
SST	Air Temperature	Swell direction
--	--	Wind wave height
--	--	Wind wave period
--	--	Wind wave direction

B. SIMULATION CONFIGURATIONS

We conduct three general types of simulations to test the influence of various mechanisms and their parameterizations on the iceberg deterioration and projected drift. Simulation scenario 1, referred to hereafter as S1, determines the sensitivity of deterioration to environmental factors. This analysis is similar to the sensitivity study conducted by Kubat et al. (2007). We estimate the deterioration sensitivity to wind speed, air temperature, current speed, water temperature, wave height, and wave period. Table 4 lists the reference values of these quantities based on the mean monthly conditions in June for the Grand Banks (El-Tahan et al. 1987). With the exception of the ocean current, the ranges of environmental values in Table 4 are based on extending the highest and lowest monthly means recorded in El-Tahan et al. (1987) to capture moderate to extreme values outside the mean. The range of current speeds is based on data from Lazier and Wright (1992), a study of annual velocity variations in the Labrador Current. In our tests, one 100-m iceberg at an arbitrary location and time is evolved over five days with user-defined environment values listed in Table 4. The input location is arbitrary, and drift is not examined for these cases as the environmental forcing inputs are set to act uniformly across the forecast period. We plot the deterioration as the loss of the waterline length over time.

In our second scenario, hereafter S2, we investigate the sensitivity to the iceberg deterioration parameters. To determine which parameters are correlated with the greatest variability in iceberg deterioration, we strive to understand the relationship between variations in the NAIS model deterioration parameters. In each test case, we vary one

deterioration parameter at a time, keeping all others at their predetermined values. Like S1, in S2 we input one 100-m, non-tabular iceberg to evolve over a period of five days. The reference values listed in Table 4 are used for the environmental forcing. Anecdotally, the NAIS 2.0 model has been noted by forecasters at CIS to, in some cases, melt icebergs at unrealistic rates. This led to a modification of the model code to allow (that is, not discontinue tracking) an iceberg whose melt exceeds 100%. In this way, forecasters can err on the side of caution that allows them to continue predicting positions of smaller icebergs. Based on the previous work, deterioration is largely caused by wave erosion (El-Tahan et al. 1987; Robe 1983; Savage 2001; White et al. 1980). Thus, we vary the iceberg perimeter affected by wave erosion, the wave erosion coefficient, and the roughness height of the iceberg surface to values listed in Table 2. We also vary the insolation and albedo, based on the wide range of possible values for these parameters (de Jong 1973; Elmes et al. 2021; Warren et al. 2019).

Table 4. Environmental data inputs for S1 and S2

Variable	Range of Values	Reference Value
Wind velocity, V_a	2 m/s, 20m/s	8.75m/s
Wind direction, Da	N/A	270°
Air temperature, T_a	273.15K, 288.15K	281.15K
Current velocity, V_w	0.1m/s, 0.5m/s	0.3m/s
Current direction, Dw	N/A	180°
Water surface temperature, T_w	273.15 K, 288.15K	279.65K
Wave direction, φ	N/A	270°
Wave period, τ	3s, 10s	7s
Wave height, H	0.5m, 5m	2m

Table note: All directions are reported in oceanographic convention

Based on the results of the sensitivity analysis, parameters with greater influences on iceberg deterioration are selected for testing in reanalysis environments to study their effects on drift in scenario 3, hereafter S3. We analyze the influence of the model parameterization on drift using a field of 175 icebergs over 32 days to determine any effects

on the behavior of iceberg populations. Icebergs are seeded to the east of Newfoundland as shown in Figure 5. This initial field is based on the iceberg distribution from the IIP daily iceberg chart for May 15, 2019. Icebergs are only seeded south of 45°N to avoid the presence of sea ice and to simplify the factors affecting drift and deterioration. Reanalysis simulations are run from 15 May to 15 June, for both 2018 and 2019. This period is chosen to avoid the presence of sea ice and because it covers the time frame when the iceberg limit begins to retreat northward due to rapid deterioration in the warming Gulf Stream current off the Grand Banks. Post-processing and display of the model output files is achieved in MATLAB. An iceberg that becomes smaller than 20m is assumed to have completely melted as deterioration parameterizations break down at such sizes. Additionally, icebergs that have run aground (as determined using the landmask of Greene, 2022) are no longer tracked.

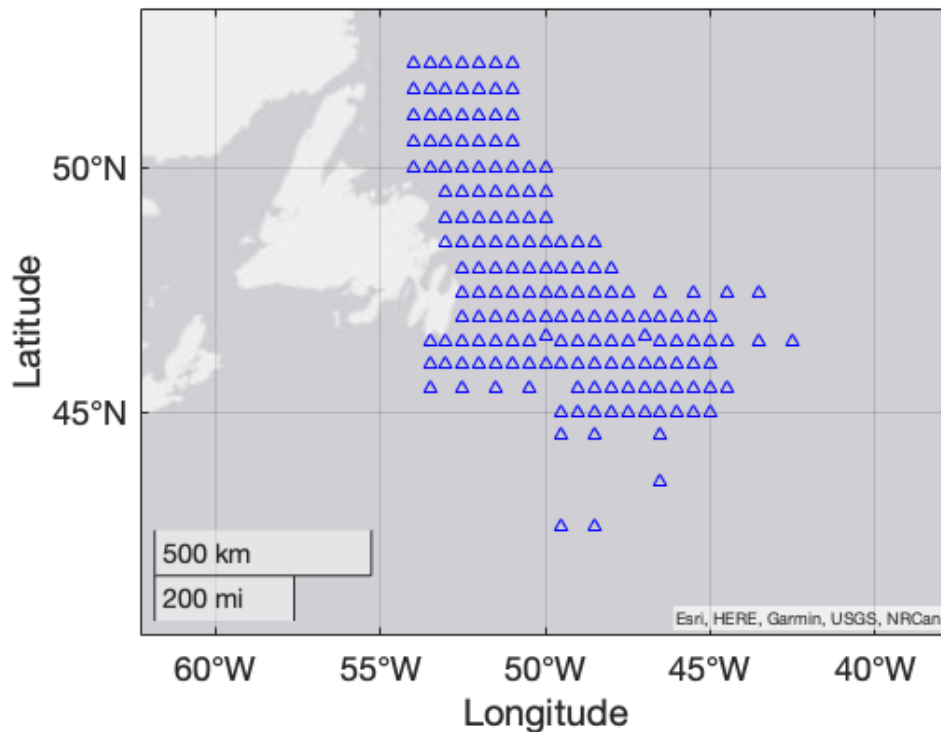


Figure 5. Seeded iceberg field for S3

IV. RESULTS

A. SCENARIO 1

Figure 6 shows how the iceberg waterline length deteriorates with time for each set of environmental variables over 120 hours. Using the upper and lower limits listed in Table 2, each environmental variable is investigated in relation to its effect on deterioration. Figure 6 shows that deterioration is most sensitive to the range of values for water temperature and wave height. It can be seen in Figure 6b that an iceberg in water temperatures of 1°C shows a mean melt rate of 1.4 m/day, but an iceberg submerged in water at 15°C results in a mean melt rate of 15 m/day, more than a factor of 10 greater. In addition, Figure 6a shows that when wave heights are increased from 0.5 m to 5 m, the mean melt rate changes from 2.0 m/day to 14 m/day. The dependence of the deterioration on wave height can be explained by its role in wave erosion and calving, which are some of the most important contributors to iceberg deterioration (El-Tahan et al. 1987; Robe 1983; Savage 2001). Figure 6c shows when the wave period is increased from 3 to 10 seconds, the melt rate increases from 4.4 m/day to 6.3 m/day. The remaining environmental variables contribute to deterioration to a much lesser degree (to within 10%). In particular, Figures 6e and 6f (current speed and air temperature, respectively) show no appreciable difference in the resultant iceberg lengths. While most of these variables are characterized by a monotonic relationship with deterioration, Figure 6d shows that the model predicts a nonmonotonic relationship between wind speed and deterioration. The reference wind speed, 8.75 m/s, results in a melt rate of 5.1 m/day, but the extreme cases of 2 m/s and 20 m/s result in melt rates of 5.3 m/day and 6.1 m/day, respectively, over the same interval. This is likely due to the influence of wind velocity, current velocity, and wave stress on the relative velocity of the iceberg, and thus, on the basal melting due to forced convection.

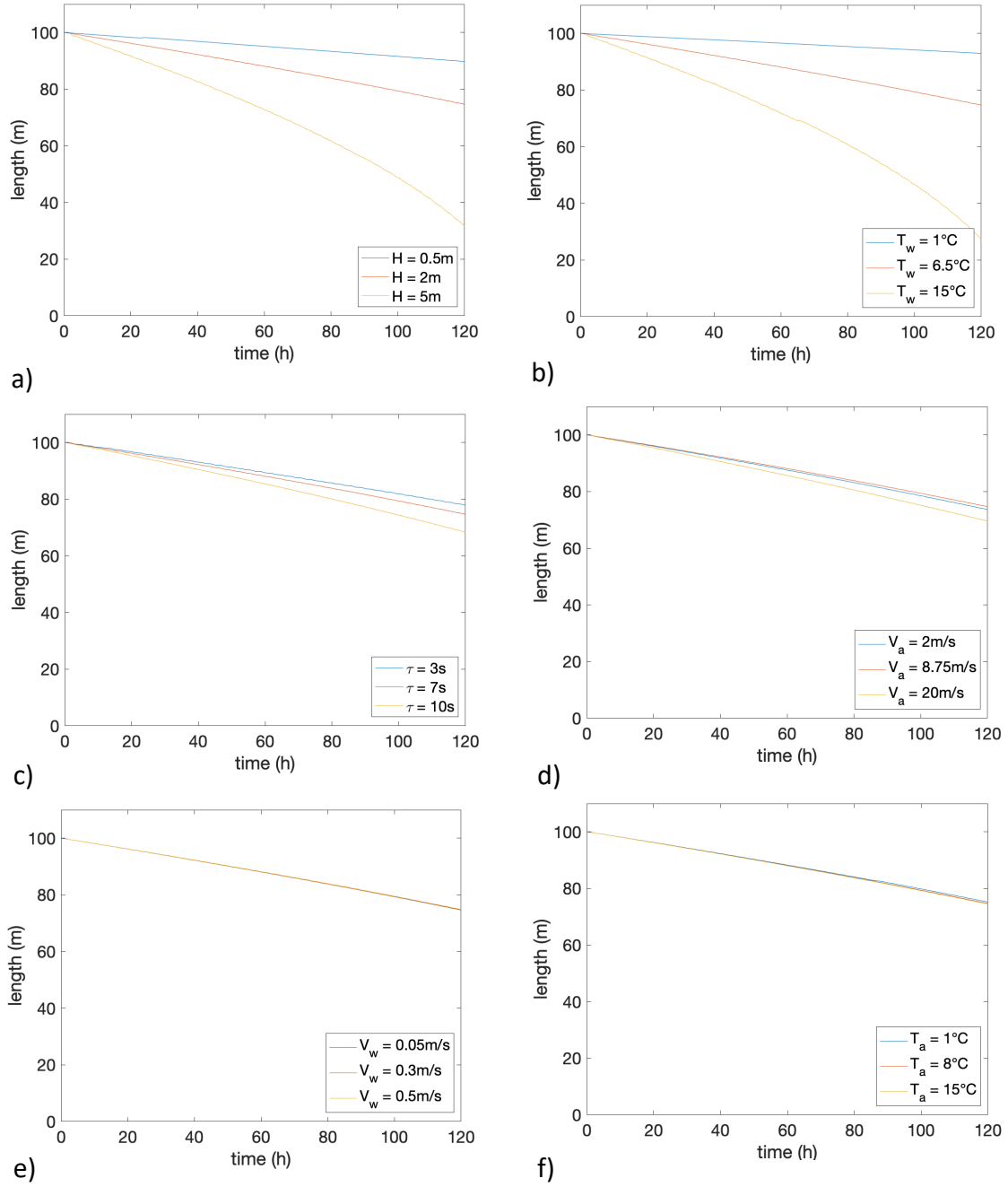


Figure 6. Each panel shows the sensitivity of the deterioration rate to a particular environmental variable: a) wave height, b) water temperature, c) wave period, d) air temperature, e) wind speed and f) air temperature

We also estimate the sensitivity of deterioration to the initial size of the iceberg. For this test, we use the reference environment in Table 4 and run the model with icebergs

of various initial lengths. We present the relative decrease in length as a function of time in Figure 7. Our results show that the deterioration rate of small icebergs is much more pronounced than that of medium-sized and large icebergs. The deterioration rates seen here are 3.16 m/day, 3.4 m/day, 5 m/day and 10 m/day for the 200-m, 150-m, 100-m, and 50-m icebergs, respectively. This relationship between deterioration rate and size can be explained by the increase in surface area to volume ratio of smaller bergs, allowing for more heat transfer to the environment. Wave erosion that acts along the waterline perimeter also has an increased influence on smaller icebergs as the perimeter to volume ratio increases. It is therefore important to investigate the long-term behavior of icebergs as a function of their size to accurately assess the deterioration of iceberg populations.

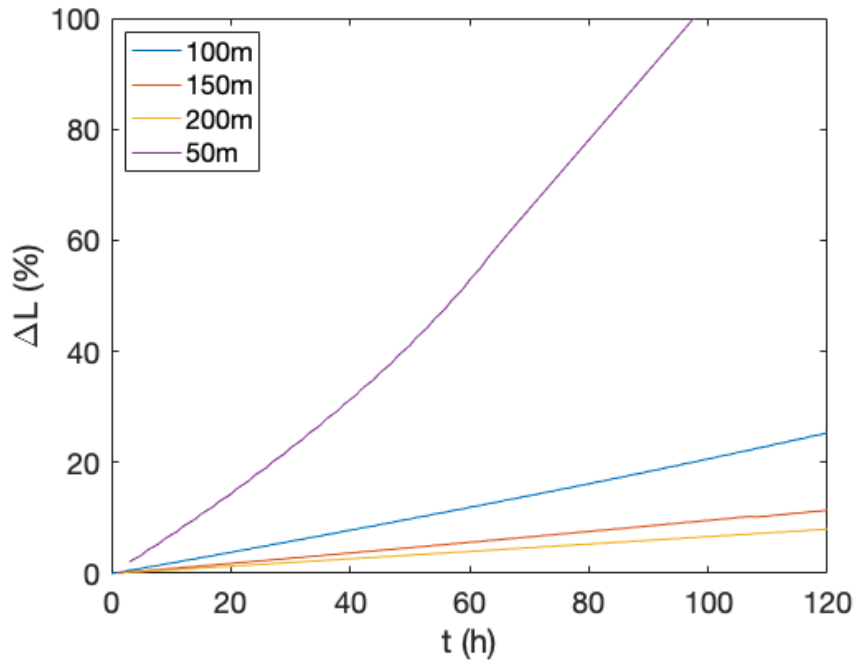


Figure 7. Sensitivity of initial iceberg length on deterioration

We investigate how the size of an iceberg affects drift in a more realistic environment by conducting similar model runs with reanalysis data from 1 June 2019 to 3 June 2019. We include the same four sizes as in the prior experiment, and each iceberg starts from the same position of 50°N 50°W. The resultant drift tracks can be viewed in

Figure 8. We find that the input size can have an appreciable influence on the modeled drift track and ending position after just three days of drift, which is consistent with prior work (e.g., Carrieres et al. 2001; Kubat et al. 2005; Robe 1983; Savage 2001). We see the largest difference between the initial 50-m and 200-m length icebergs, while the two larger icebergs have the smallest difference in final position. We expect this is due to the relationships in Equation 2.1, which explain how wind and water drag forces, as well as the wave radiation stress, affect small versus a very large mass.

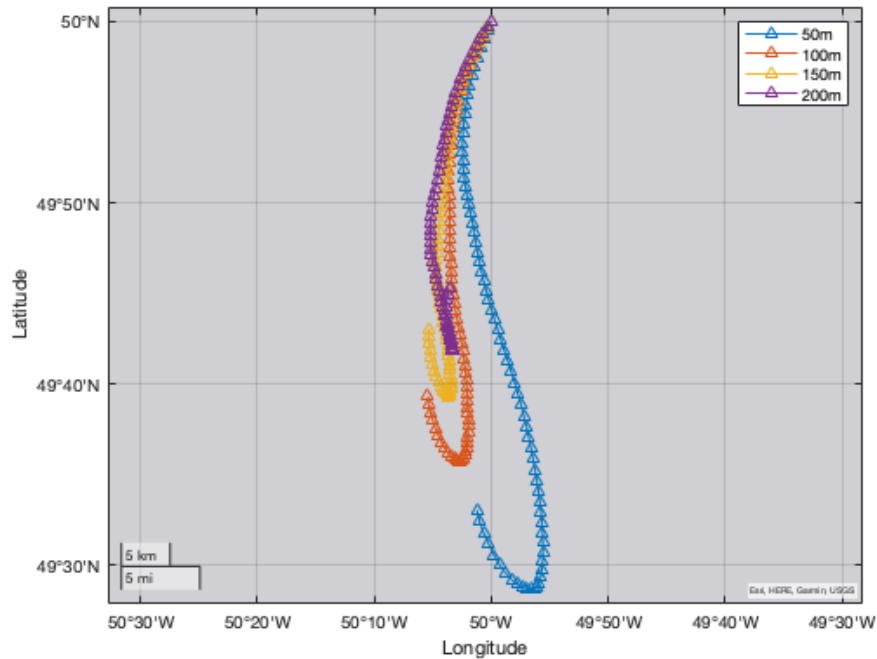


Figure 8. Influence of initial waterline length on predicted drift trajectory

B. SCENARIO 2

S2 cases show the sensitivity of iceberg deterioration to wave erosion and surface melting parameters over five days. Figure 9 displays the waterline-length deterioration as a function of time for different values of the wave-eroded perimeter, P , and the wave erosion coefficient, C . The chosen values for the coefficient are expressed in terms of the reference value, C_0 . The 100-m iceberg shows a melt rate of 5.1 m/day for canonical

values. Reducing the wave-eroded perimeter from $3L$ to $1.5L$ leads to a 36% decrease in melt rate. We attribute this significant change due to wave erosion being the largest overall contributor to deterioration (El-Tahan et al. 1987; Savage 2001; White et al. 1980). Increasing the value of the wave erosion coefficient by 10% increases the melt rate by 7%, while decreasing the coefficient by 10% decreases it by 8%.

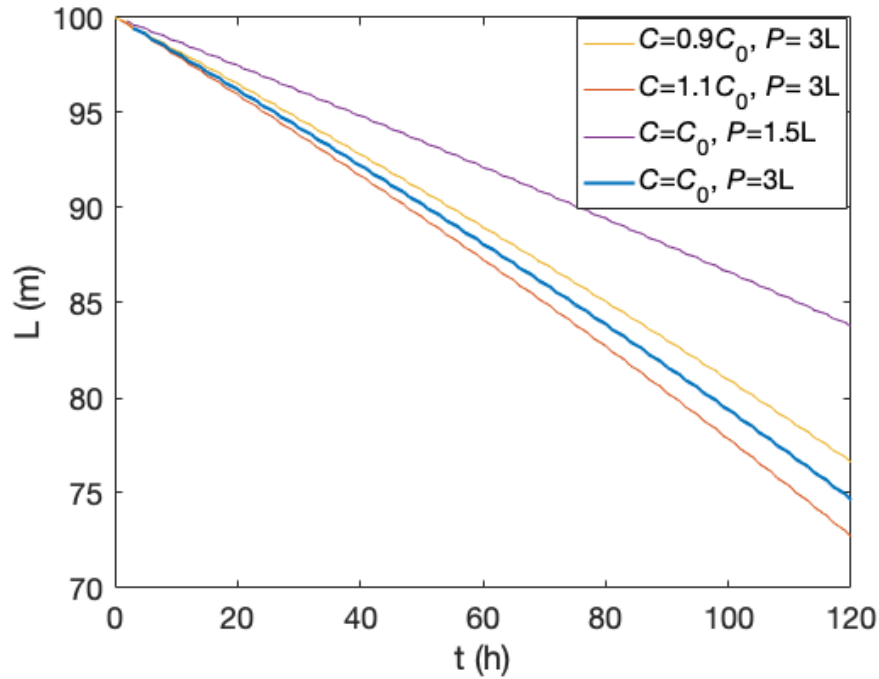


Figure 9. Effect of wave erosion coefficient, C , and eroded waterline perimeter, P , on deterioration of the waterline length.

The waterline deterioration sensitivity to variations in roughness height, R , are shown in Figure 10. The mean melt rate for a roughness height of 0.5cm was 4.4m/day and for 2cm was 5.8m/day. Doubling the roughness height from 1cm to 2cm increases the mean melt rate by 15%, whereas the reduction of the roughness height by half from 1cm to 0.5cm results in a 13% decrease in melt rate. This result is expected based on Equation 2.3, which reveals the lack of coupled processes and suggests a simple dependence on the roughness height. As higher roughness heights increase convective heat transfer (White et al. 1980)

during wave erosion, it follows that increasing this value will lead to greater melt. This result is also fully consistent with Equation 2.3.

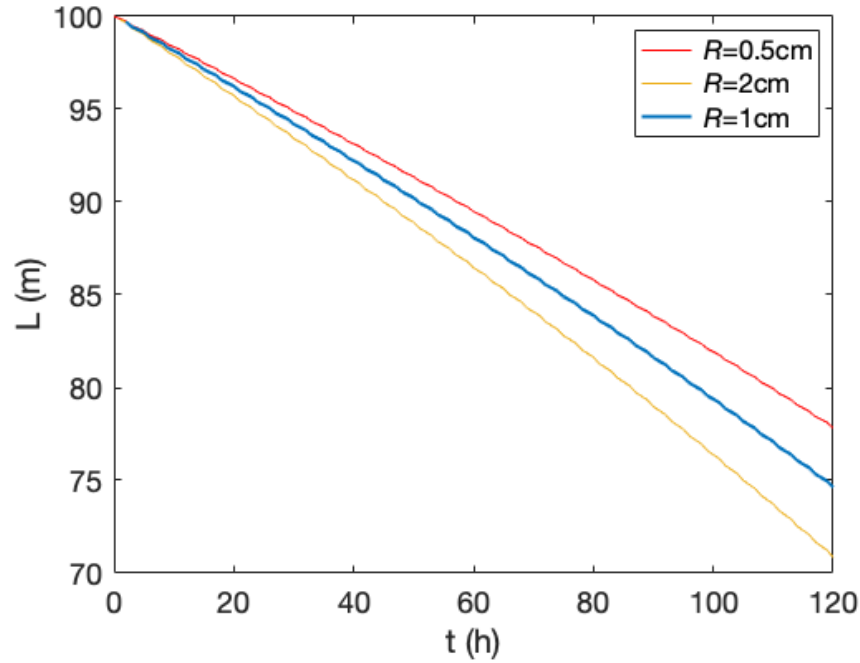


Figure 10. Effect of roughness height of the iceberg surface on deterioration of waterline length

Figure 11 shows the waterline deterioration for simulations with varying values of the surface melting parameters, I and α . Though the value for insolation varies greatly across a season from 15 to 350 W/m², Figure 11a shows a negligible difference in the deterioration of an iceberg. Similarly, Figure 11b shows that although albedo may also take on a range of values but, similarly, we find its effect on deterioration negligible. These results are due to the impact of surface melting being only up to 0.3 – 5% of total deterioration.

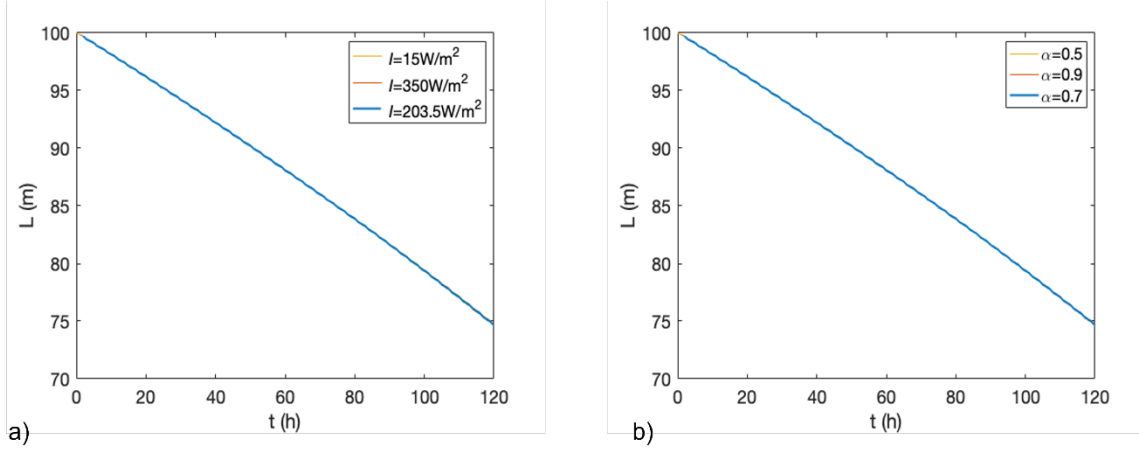


Figure 11. Effect of a) insolation and b) albedo variations on deterioration of waterline length.

C. SCENARIO 3

S3 cases investigate the effect of deterioration parameterization on the iceberg drift. We visualize the distribution of the iceberg field from our simulations using the density plot overlaid on geographical features. To generate these plots, we use a smoothing radius of 50km, which is comparable to our initial iceberg spacing. As such, higher densities indicate an increased occurrence of simulated icebergs near a particular location. An asterisk indicates the weighted center of the initial position of the seeded iceberg field and a line connects the initial weighted center to the ending position weighted center. The equation for the weighted center is:

$$\vec{x}_c = \frac{\sum_{i=1}^N \vec{x}_i}{N}, \quad (4.1)$$

where N is the number of icebergs, $\vec{x}_i$ is the position of any given iceberg and $\vec{x}_c$ is the iceberg field center.

The error bars on the density plots indicate the spread in ending iceberg positions, shown as the standard deviation about the ending position weighted center. The equations for this latitudinal and longitudinal deviation about the weighted center are:

$$\sigma^2_{lat} = \frac{\sum_{i=1}^N (y_i - y_c)^2}{N}, \quad (4.2)$$

$$\sigma^2_{lon} = \frac{\sum_{i=1}^N (x_i - x_c)^2}{N}. \quad (4.3)$$

Figure 12 shows the model runs seeded with small, medium, and large icebergs with canonical parameter values. The drifting lifespans (duration until melting or becoming grounded) of small icebergs average to 9 days, the medium icebergs, 19 days, and the large icebergs, 26 days. Thus, there is a strong relationship between the initial size and observed density patterns due to the increased drifting lifespan with larger icebergs. Figure 12a shows that the small iceberg ending position center deviates the least from the initial position. The medium-sized icebergs drift 61km further southwest on average, which is shown in Figure 12b. Some of this difference could be due to their shorter cumulative lifespan. Figure 12c shows that the large icebergs drift further south of Newfoundland. This effect is likely influenced by their longer lifespan leading to a broader drift pattern. The ending position center of the large icebergs is 25 km west of the medium case. In all cases, we notice the distribution of icebergs is concentrated within the Grand Banks, the extension of the continental shelf southeast of Newfoundland, and densities abruptly decline outside of the continental shelf where the warm North Atlantic Current is encountered.

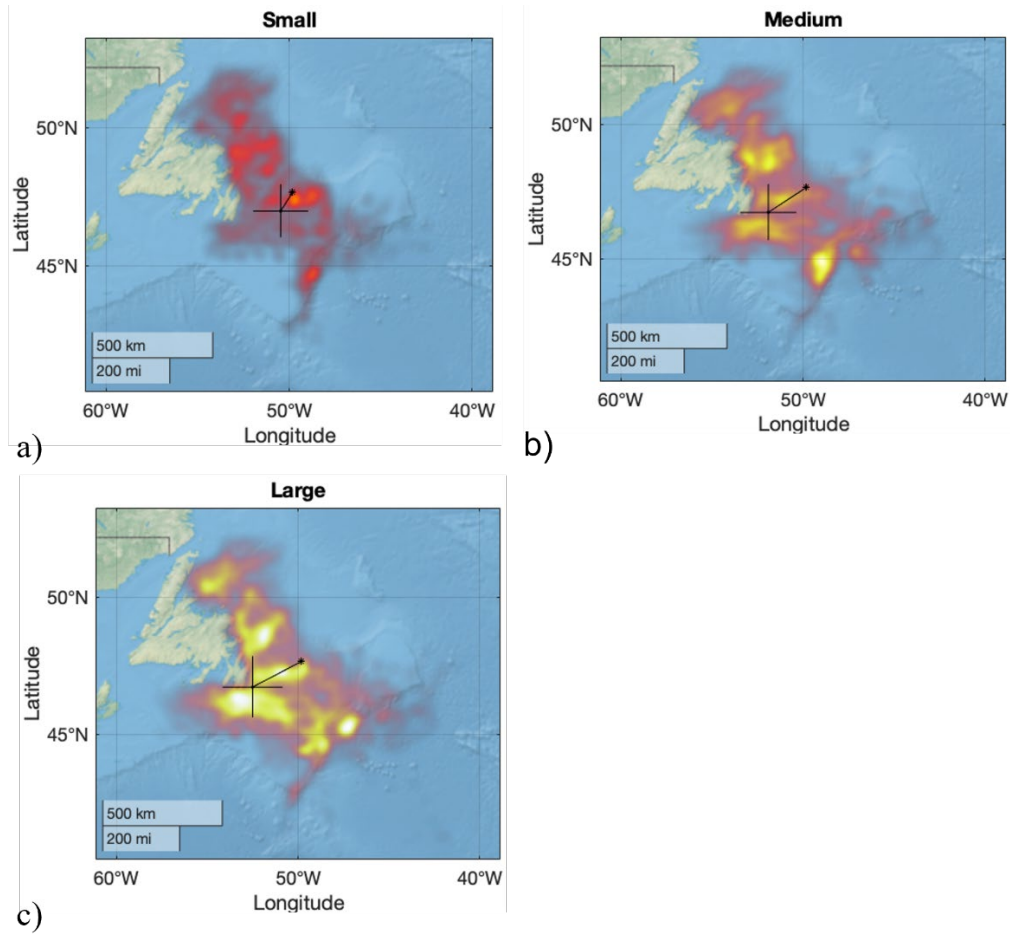


Figure 12. Effect of initial iceberg size on density distribution after 32 days. Figure a) began with small icebergs, b) began with medium icebergs, and c) began with large icebergs.

Based on the foregoing investigation of the parameter sensitivities, we test the sensitivity of P , R , and C for their respective effects on drift. These cases all begin with medium icebergs, and therefore, the medium case shown in Figure 13a, where parameters are set to their default values, will act as a reference. Figure 13b shows the results of using $P = 1.5L$ as the waterline perimeter eroded by waves. We notice an increased density of icebergs, which is explained by the average drifted lifespan being 6 days greater than the reference. This case also shows the largest difference in the ending position center of mass, which is 50 km southeast relative to the reference case. There is also a small, but noticeable increase in the spatial extent to the south of St. John's, as well as in the eastern part of the domain; we attribute this broader iceberg distribution to the larger number of drifting days.

The tests for R and C , Figures 13c–f, exhibit insignificant changes to the modeled drift relative to the reference case. The final field center for $R = 0.5\text{cm}$ is separated by 5.4 km from the reference and the center for $R = 2\text{cm}$, is 32 km from the reference. The resulting differences in the weighted center from the reference for $C = 0.9C_0$ and $C = 1.1C_0$ are 14 km and 20 km, respectively. The average drifting days for all R and C cases are within 2 days of the reference simulation.

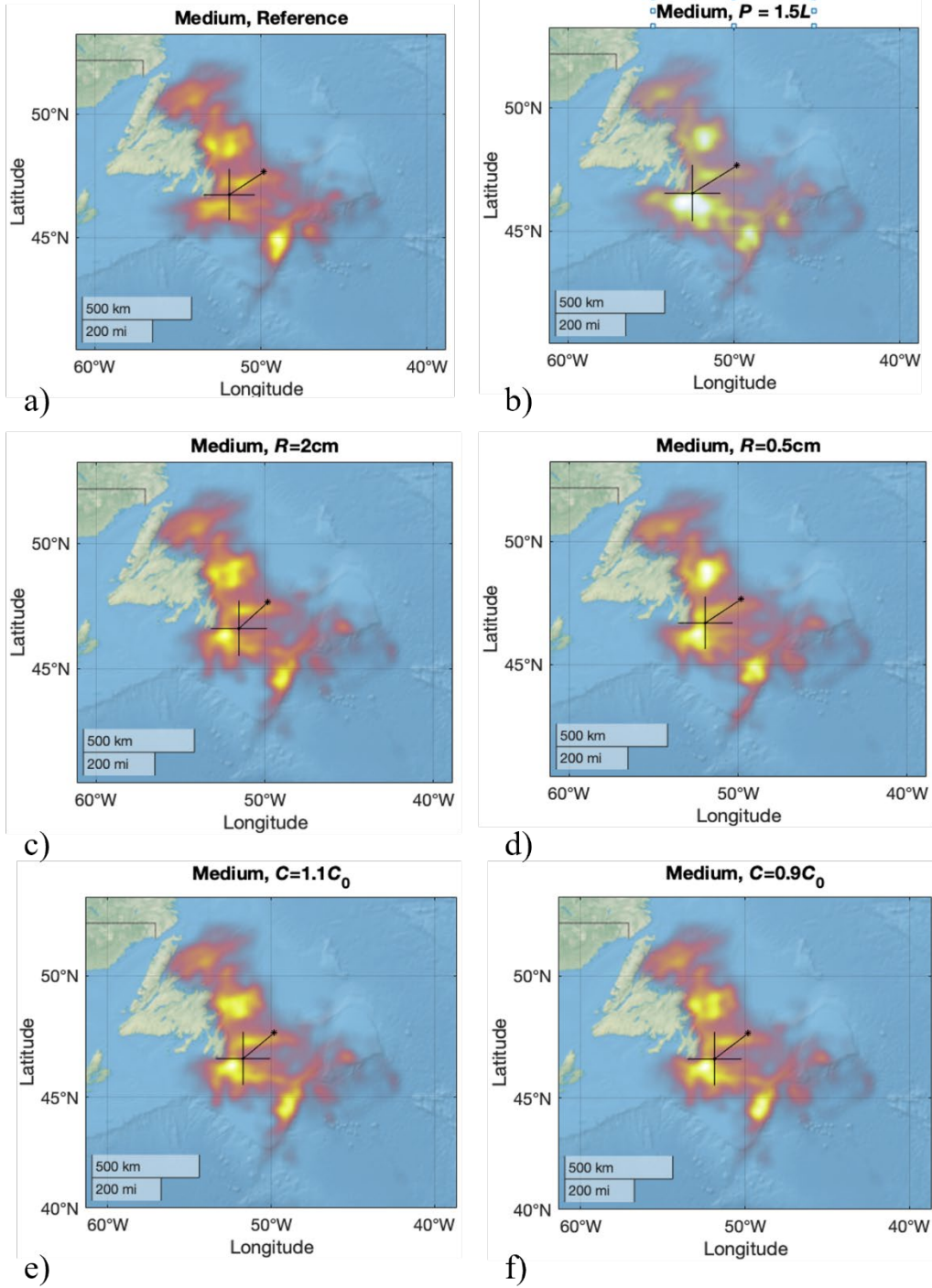


Figure 13. Effect of deterioration parameters on iceberg drift. Panel a) reference case, b) $P=1.5L$, c) $R=2\text{cm}$, d) $R=0.5\text{cm}$, e) $C=1.1C_0$, and f) $C=0.9C_0$.

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V. DISCUSSION AND CONCLUSIONS

We have employed the NAIS 2.0 Model to simulate iceberg deterioration and drift. In particular, we quantified 1) the influence of environmental factors, 2) the sensitivity of specific deterioration parameters, and 3) the effect of deterioration parameterizations on the drift of an iceberg field. We find that the water temperature and wave height have the largest impact on deterioration. Water temperature affects numerous deterioration mechanisms as it controls wave erosion, calving, water forced convection, and vertical buoyant convection. The wave height contributes to wave erosion and calving, which other studies have shown to be the largest contributors to deterioration (El-Tahan et al. 1987; Kubat et al. 2007).

The waterline perimeter affected by wave action has a significant impact on the modeled melt rate with up to a 36% decrease when this parameter is assigned its lower physical limit. It should be noted that the model prescribes the expression of P in terms of the waterline length, and therefore its dependence on iceberg geometry has not been explored in this thesis. For the other wave erosion parameters, R and C , we find that roughness height has a minor, but not insignificant, effect on the deterioration rate. If the roughness height of the iceberg surface is correlated with wave height, as suggested by Robe (1983), then much higher roughness heights are possible. This would have a greater influence on deterioration than reported here. Changes in the wave erosion coefficient, C , show moderate effects on the deterioration rate, but a negligible change in drift. However, as an empirical value, changes in the form of other wave erosion parameters may alter the value for C and thus it should be evaluated in tandem with other parameters and validated with laboratory and field measurements.

After testing the full range of possible values for insolation, we find its impact on melting is entirely negligible. Likewise, albedo can also take on a range of values, but it does not influence the iceberg melt. We believe the model is insensitive to these values because they only affect surface melting, which at most comprises a meager 5% of total deterioration (Savage 2001).

Lastly, we find only the initial input size and the wave eroded perimeter have an appreciable impact on drift trajectory. There are clear differences in both the temporal extent (iceberg lifespan) and spatial extent in the drifted fields of small, medium, and large icebergs. The small icebergs drift the least from their starting point, while the medium and large fields weighted centers drifted comparably. We note that there was an opposite relationship when modeling individual iceberg drift over three days—the smallest iceberg drifted furthest from the initial position. We believe that patterns of extent in the density plots reflect that icebergs with longer lifespans drift further, and thus have greater extent, whereas most of our small icebergs melt completely during the test period, which stunted the aggregate field drift. These results reinforce earlier studies that emphasize the influence of iceberg size on drift (Robe 1983; Kubat et al. 2005; Savage 2001). Similarly, reducing the wave-eroded perimeter approximation by half leads to average lifespans similar to large icebergs, yet the difference in ending position from the reference medium field is twice the value of the large field compared to the medium.

While iceberg modeling has progressed greatly in recent decades, there is still much room for improvement. Namely, more laboratory and field studies that include measurements of deterioration and iceberg geometry will assist in fine-tuning model processes. Future work should investigate icebergs with various perimeters subject to wave action to better constrain this value and determine dependencies on an iceberg shape. We also suggest that future studies determine any such relationship between waves and the roughness height and, if necessary, construct a prescription for this value. In addition, as White et al. (1980) suggested, future work should investigate the overall relationship between how roughness height parameterization influences wave erosion and calving. Furthermore, expansion of the utility of the model to other regions such as the Denmark Strait (passage between Greenland and Iceland) and the Antarctic could improve operational planning in these regions. At the time of this thesis, NRL is working with the USNIC to adapt and validate the NAIS 2.0 model for Antarctic applications. The Argentine Ice Service is also working to make NAIS 2.0 valuable for predicting Antarctic iceberg drift. Future work may focus on the Antarctic domain and on understanding how drift and deterioration processes differ between the Arctic and Antarctic.

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