

Iceberg Melting and Climate Change in NW Atlantic Waters

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ABSTRACT: Climate change is predicted to cause increases in sea surface temperature (SST), as well as decreases in sea-ice cover, wind and current velocities. These changes will have a marked effect on iceberg melting in the shipping lanes off Newfoundland and Labrador, Canada.

Icebergs that today can cross from northern Labrador to Newfoundland without melting will in the future have to be much larger to survive the transit. For example, icebergs at N Labrador in December of 2016 that are smaller than 156 m will melt before reaching 48N, but in year 2100 the length increases to 228 m. In addition, if future iceberg size distributions off Labrador are the same as today, icebergs will experience roughly 50% reductions in numbers in the NW Atlantic shipping lanes by year 2100.

The increased melting rates are due to, in order of importance, increased sea-surface temperatures (responsible for 66% of the increase in the minimum transit size), decreasing current velocities (31%), and decreasing sea-ice cover (3%). Decreasing sea-ice tends to increase wave heights as well as accelerate the effects of wave erosion; however, for the areas studied the wave height is predicted to decrease moderately in year 2100, by a maximum of about 10% in December.

1 BACKGROUND

Since the sinking of the passenger ship Titanic in 1912, the International Ice Patrol (IIP) has kept watch in waters off Newfoundland, south of 48N latitude and east to about 40 west longitude. Here icebergs threaten off-shore oil rigs, fishing boats and commercial ships on their way to Europe and Africa.

In this work we investigate the effects of climate change on icebergs in the NW Atlantic. Increasing sea surface temperatures, decreasing current velocities, winds and sea-ice will be shown to have a significant effect on the melting of icebergs.

Greenland's sea/glacier interfaces are the main source of icebergs floating into the NW Atlantic shipping lanes off Newfoundland. These icebergs

typically move northward with the West Greenland Current after calving, then south along the Labrador and Baffin Island coasts until reaching the shipping lanes at the 48th parallel off Newfoundland – a 3000 to 4000 km journey that can take years to complete (Canadian Coast Guard, 2012). Figure 1 shows the normal iceberg trajectories, as well as the major Greenland calving locations. For scale, the distance from the southern tip of Greenland to the northern end of Baffin Bay is about the same as from Florida to New York, U.S.A.

Iceberg drift studies by Marko et al. (1982), Robe and Maier (1979), Robe et al. (1980) followed icebergs from the east coast of Baffin Island down to as far as 48 N latitude near Newfoundland. Of all the icebergs tracked, only two came close to 48N –

icebergs number 160 and 344 (Robe and Maier (1979) and Robe et al. (1980)). As far as we know these two bergs had the longest observed runs of any iceberg tracked in the NW Atlantic, from 67°N down to about 48°N, at roughly 150 km from shore.



Figure 1. Track followed by icebergs after calving. Image from Canadian Coast Guard (2012).

Only a small portion of icebergs calved in Greenland are estimated to make it to the shipping lanes south of the 48th parallel, succumbing to prolonged groundings and eventual melting. No iceberg has ever been followed from its birth to the shipping lanes. In Nalcor (2015), the authors document that more than 90% of the icebergs drifting south from northern Labrador to 48°N do so within about 6 degrees of longitude of the shore, a distance of roughly 360 km.

There is great year-to-year variability in the numbers of icebergs drifting into the shipping lanes. Yearly iceberg numbers can range from none to more than 2000. Peterson et al. (2000) and Marko (1984) found that sea-ice extent was the most important factor in correlating iceberg seasonal variability. Wind direction has also been shown to be important, as easterly winds tend to move icebergs towards shore. The prevailing wind direction however is from the WNW (Nalcor, 2015). Peterson et al. (2000) and IIP (2015) studied the effect of the NAO (North Atlantic Oscillation). They found a strong link between NAO index and iceberg totals. Newell (1991) proposed that variability in yearly iceberg numbers may be influenced by the break-up of huge ice islands that

periodically drift into the waters off Labrador and Newfoundland. Bigg et al. (2014) proposed that yearly variability in iceberg numbers in the shipping lanes may be caused by variability in iceberg calving at glacier termini.

White et al. (1980) conducted a review of ice melting literature as well as wave erosion experiments in a tank. They used these data with dimensional analysis to develop equations for iceberg wave erosion, forced convection, and the failure length of overhanging slabs that are cut into iceberg surfaces by wave erosion. These slabs result in calving when they reach the failure length, but the failure length equation of White et al. requires knowledge of the overhanging slab thickness, which was beyond the scope of the work by White et al. Savage (1999) developed an equation for the thickness of overhanging slabs, permitting relatively simple iceberg calving calculations using White's equation. EL-Tahan et al. (1987) used observations of icebergs off Labrador and the Grand Banks to test White's methods, considering buoyancy-driven (natural) convection, water forced convection, wave erosion, and calving (it is unclear from their paper how the thickness of the overhanging slab was calculated). The authors found the parametrizations outlined in White et al. (1980) resulted in good agreement with observed data. EL-Tahan also found that neither insolation nor air/iceberg heat transfer play a significant role in NW Atlantic iceberg melting.

Since White's paper was published, some form of his equations have been adopted by the International Ice Patrol and the Canadian Ice Service for predicting iceberg drift and deterioration. To reduce computational time, simplified equations for iceberg melting have been used by Bigg (1997, 1996) and Wagner (2017) to model long-range drifts of large numbers of icebergs. In particular, wave erosion predictions were made a function of the sea state only, independent of SST (sea surface temperature).

Han et al. (2015) used Global and Regional Climate Models (GCMs and RCMs) to predict reductions in iceberg numbers due to climate change. They extrapolated a correlation between air temperature at Labrador and icebergs below 48°N to the climate-model-predicted air temperatures, in order to determine future iceberg numbers in the shipping lanes. The authors used a conservative assumption for CO₂ emissions (Representative Concentration Pathway 4.5 (RCP4.5) as well as a more aggressive emissions scenario (RCP8.5). The authors found that, relative to the 813 iceberg mean from 1981-2010, icebergs below 48°N would decrease by 30% to 100% by the year 2060.

CESM1-CAM5 is the highest-rated climate model by Knutti et al. (2013). The authors evaluated 38 models from World Climate Research Programme Coupled Model Intercomparison Project Phase 5 (CMIP5).

RCP8.5 is an acronym for Representative Concentration Pathway, a future greenhouse gas emission scenario sometimes referred to as a "business as usual" model. In RCP8.5, emissions continue to rise to a CO₂ concentration of about 940 ppm. Actual greenhouse gas emissions have most

closely matched RCP8.5 of all the scenarios tested (Alexander et al., 2018).

In this work we use predictions from climate models with the RCP8.5 emission scenario to determine what effect changing environmental parameters will have on the melting of icebergs off Newfoundland and Labrador, and to estimate changes in future iceberg numbers drifting into the NW Atlantic shipping lanes.

2 METHODS

2.1 General

As mentioned earlier, icebergs can take years to cover the distance from calving sites to shipping lanes. Icebergs have not been followed over the entirety of their journey, and thus important details such as drift velocities, paths followed and grounding frequencies are unknown.

Due to this paucity of information, we consider only future iceberg melting from northern Labrador to Newfoundland. This is a geographical area that has been thoroughly studied by the oil and gas industry. Nalcor (2015) presents historical averages of winds, currents, ice cover, wave heights, ship icing, sea temperatures, icebergs and visibility off Labrador and Newfoundland.

Our analysis is based on what can be considered an average iceberg path off Labrador and Newfoundland, between 60N and 48N, at about 2.5 degrees longitude off-shore (a distance of about 150 km), along a path similar to Robe's icebergs 160 and 344. Nalcor (2015) found that greater than 90% of the icebergs drifting south along Labrador and Newfoundland shores do so within about 5 degree of longitude off-shore, on average.

The distance off-shore has a very important effect on iceberg melting rates. Icebergs within about 1 degree longitude may experience very slow drift velocities, sometimes in directions opposing the normal north-south movement of the Labrador current (Nalcor 2015). In addition, sea-surface temperatures are considerably warmer off-shore, where the influence of the warm northerly flowing North-Atlantic current is more pronounced. The extent of sea-ice cover is also greatest near-shore, which tends to protect icebergs by decreasing wave heights as well as protecting them from the effects of wave erosion. Waves tend to be larger off-shore, along with higher wind speeds.

The result is that, assuming equal drift velocities, icebergs are more protected from melting when they are closer to shore. But the reality may be that these icebergs are much less likely to survive the journey due to groundings and excessive exposure time. Initially it was our goal to analyze iceberg melting for paths close to shore (icebergs within 1 degree of longitude to Labrador and Newfoundland shores constitute about 10 percent of all bergs moving south) as well as off-shore, but such an effort would be plagued by too much uncertainty in transit times from 60N to 48N. More iceberg observations are required.

Our scheme involves allowing icebergs to drift in one-day increments (or time steps) beginning at 60N, and then using a melting model to determine iceberg size at the end of the time step. The melting model requires input of environmental parameters such as SST, ice fraction and wind speed. These were averaged over an area encompassing Labrador and Newfoundland shores out to about 5 degrees of longitude from the shore, as a function of the month, and parametrized in trendlines. Wave heights are calculated at each time steps using relations we derived, as a function of wind speed and sea-ice coverage. In the following sections we provide further details dealing with environmental parameters as well as our melting model.

2.2 Climate data

Climate model CESM1-CAM5 results were downloaded from the Center for Environmental Data Analysis website (NCAR, 2017), and used to estimate future average sea-surface temperature (SST), winds, y-component current velocities (north to south) and sea-ice coverage in Labrador and Newfoundland waters. These were averaged in the area between the shoreline and about 6 longitude degrees east of the shore. Trends were averaged monthly, over 20-year periods between 2006 and 2025 (referred to as CESM1 year 2016 average), and between 2081 and 2100 (referred to as CESM1 future or year 2100 averages). Wind trends were determined over 15 year-periods (2006-2020, and 2086-2100), as these had a much smaller year-to-year variance.

Climate model results were downloaded and analyzed with a Linux version of Panoply (NASA GISS, 2018).

We refer to the difference between CESM1 future and CESM1 current environmental values as the CESM1 anomalies. These were added to observed 20-year average parameters, calculated from environmental data from HadISST (2003) in the same way as the CESM1 data, yielding predicted year 2100 environmental averages. HadISST (2003) data includes past SST, ice cover and winds. Wave heights over the past 20 years were obtained from Nalcor (2015).

Year 2100 Drift Velocities and Crossing Times: We first construct a plot of year 2016 drift velocity in the y-direction as a function of the month by plotting the velocities of Robe's 340 and 160 icebergs on Figure 2 (yellow squares), and then scaling the CESM1 year 2016 plot to those points (Robe 2016 on Figure 2). This plot is then moved down by the same amount as the CESM1 2100-2016 anomaly (the difference between the CESM1 2016 and CESM1 2100 plots on Figure 2), resulting in year 2100 predicted average drift velocities in the y-direction (dashed blue line on Figure 2).

Velocities for Robe's 160 and 344 icebergs were measured in 1977 and 1978, and we used these as sea-current velocities in 2016 for our analysis. We felt this was justified, as applying the CESM1-calculated average rate of change of current velocity from 2006 to 2026 to the 1977 and 1978 observations resulted in a

relatively small changes in drift velocity between 1977/78 and 2016.

The drift time required to make the 1350 km journey (distance in y-direction from 60N to 48N) was calculated by numerically integrating $\int V_y dt$ in time steps of 0.2 days until 1350 km were traversed, using the “Robe 2100” plot from Figure 2 for year 2100 and the “Robe 2016” plot for year 2016.

Figure 3 shows the crossing times (generated by observed and calculated drift velocities) for years 2100 and 2016, from 60N to 48N latitude, as a function of month initiating the crossing. The plot shows increases in transit times ranging from 6 to 13 days, with the largest increases in winter months.

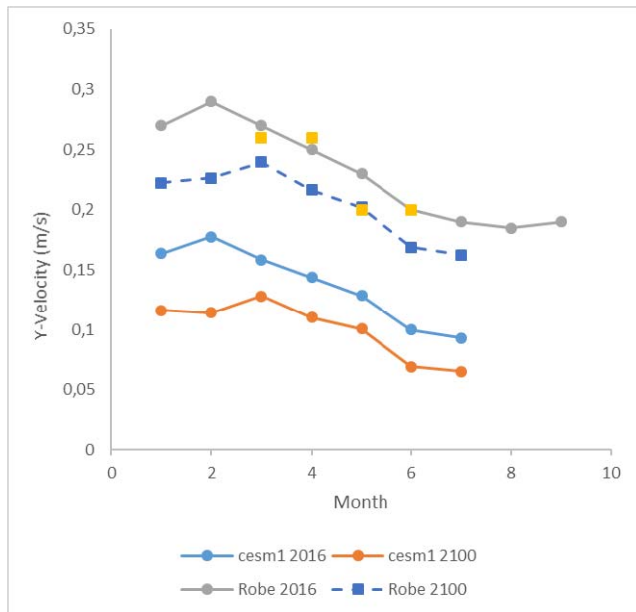


Figure 2. y-direction current velocity. The lower 2 lines are the CESM1 year 2100 and year 2016 y-direction velocities. The difference between these two (the CESM1 anomaly) is the amount by which the year 2016 y-velocity (top line) is reduced, resulting in the year 2100 average drift velocity (blue dashed line).

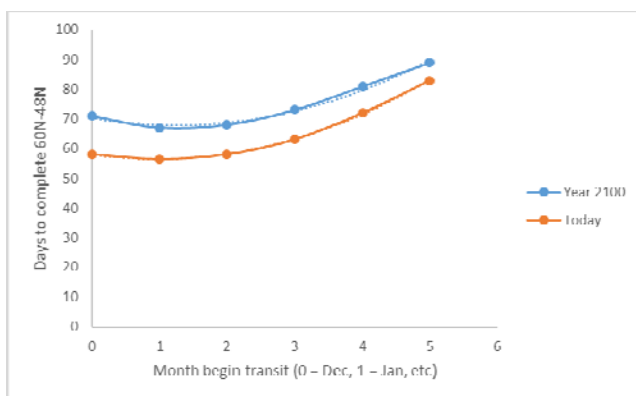


Figure 3. Days to complete the transit from 60N to 48N latitude along a typical iceberg path in years 2016 and 2100.

2.3 Sea Surface Temperature (SST)

CESM1 predicts an increased sea surface temperature (SST) in year 2100 of 2.3 to 0.75 degrees C. Figure 4 shows the biggest increases are in December, January, July and August.

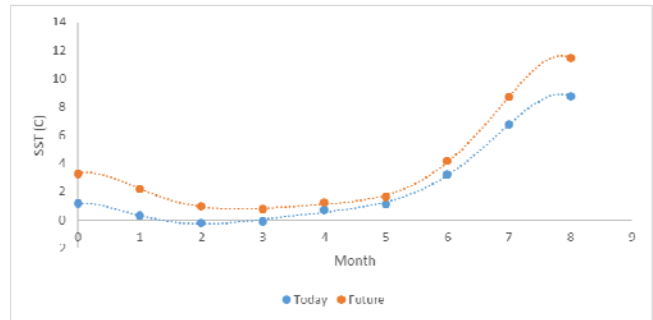


Figure 4. Sea-surface temperatures (SST) for years 2100 and 2016, averaged in waters off Labrador and Newfoundland.

2.4 Sea-Ice Coverage

Figure 5 shows a significant decrease in sea-ice cover in the winter months by year 2100. This decrease tends to lead to increased wave heights and decreased protection of icebergs by sea-ice. But, as will be shown in a later section, this difference is not very important in overall iceberg melting, as the mitigating effects of ice fraction on wave height and wave erosion are greatest above 85% ice cover, and relatively small below this.

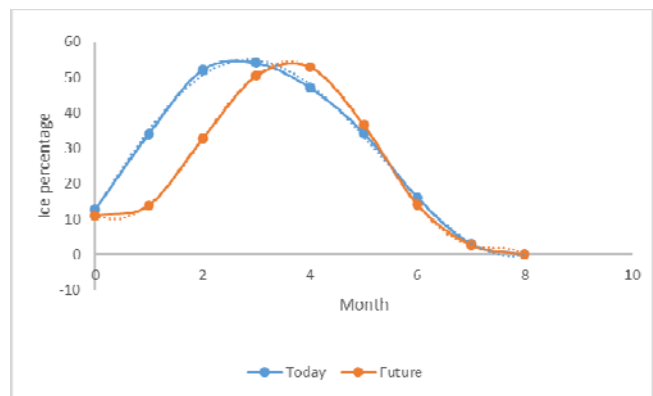


Figure 5. Sea-ice percentage for years 2016 and 2100, averaged in waters off Newfoundland and Labrador.

2.5 Winds

Winds can move icebergs relative to the surrounding water, causing forced convection heat transfer. In addition, winds directly affect wave heights. Figure 6 shows a slight decrease in year 2100 wind speed, averaged in waters off Newfoundland and Labrador.

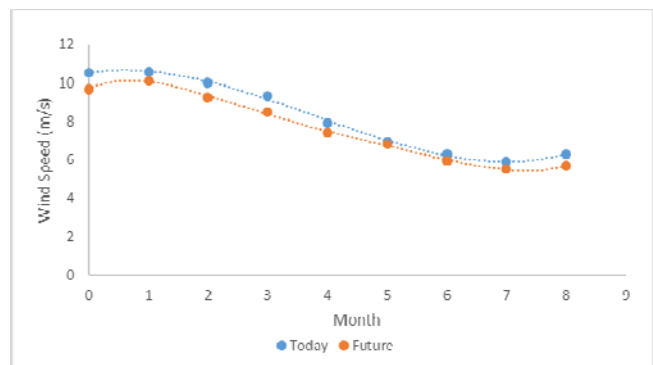


Figure 6. Wind speeds off Newfoundland and Labrador for years 2016 and 2100.

2.6 Wave heights

Equations for wave height as a function of wind speed, ice coverage and fetch were developed using dimensional analysis and historical environmental data.

Wave heights are known to depend on wind speed, sea-ice coverage and fetch. The Buckingham pi theorem (White, 2016) then dictates two dimensionless groups can describe wave height results. Using a trial and error process these equations were found to be:

$$H^* = \frac{\text{fetch} \times \cos(1 - \text{ice fraction})}{\text{wave ht}} \quad [1]$$

where H^* can be considered a dimensionless wave height, fetch is the distance off-shore along a parallel of latitude, ice fraction is the fraction of the sea surface that is covered by sea-ice, and wave ht is the wave height, in the same units as the fetch. Also, we define a dimensionless fetch F^* :

$$F^* = \left(9.8 \text{ fetch} \right)^{\frac{1}{2}} \times \cos(1 - \text{ice fraction}) / (\text{wind speed}) \quad [2]$$

We note that the 9.8 is the gravitational constant in m/s^2 .

Figure 7 shows a plot of H^* as a function of F^* . A 3rd degree polynomial trendline fits the wave data from Nalcor (2015), for years 1954-2013, from winter, spring and summer seasons with R^2 value of 0.74, from $\frac{1}{2}$ degree of longitude east of the shoreline to an average of 5 degrees (4 degrees east at 58-60 N, 5 degrees from 52-56N, and 7 degrees at 49N). This ensured capturing greater than 90% of all the icebergs transiting south along Labrador and Newfoundland shores (Nalcor, 2015).

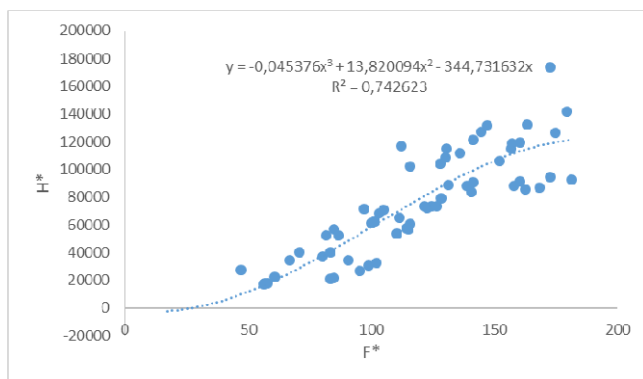


Figure 7. Dimensionless wave height H^* as a function of dimensionless fetch F^* . F^* values between 40 and 100 are within 1 degree of longitude from the shore. The remaining points are at a variety of fetch values from 30 to 300 km. The dotted line shows the trendline.

The trendline generated was:

$$H^* = -0.045376F^{*3} + 13.820094 F^{*2} - 344.731632 F^* \quad [4]$$

The trendline achieves a reasonable fit to the data, as shown in Figure 8 below:

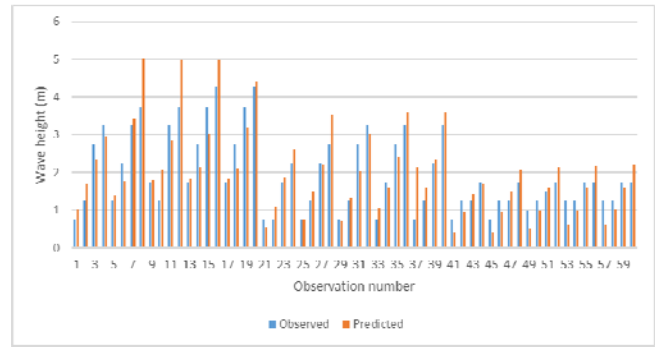


Figure 8. Predicted and observed wave heights using equations (1)-(4).

The large absolute magnitude errors at observation numbers that are multiples of 4 are at the furthest fetch, corresponding to about 5 degrees of longitude from the shore.

Figure 9 shows the wave heights at 2.5 degrees from shore, as well as at 0.5 degrees, for years 2016 and 2100, using our wave height relation with predicted (2100) and observed (2016) environmental data. Moderate decreases in wave height are seen in year 2100, due to wind speed reductions. Reductions in ice cover, although large (for example, in January, ice cover drops from 34% in year 2016 to 14% in 2100), occur at ice fractions that are low enough so as not to cause significant increases in wave height.

The near-shore wave heights also merit contemplation: wave heights in December, when there is very little ice present today, show a decrease in height in year 2100 due to reduced wind speeds. However, by January and beyond, when currently significant ice is present, the decrease in year 2100 ice cover results in increased wave heights.

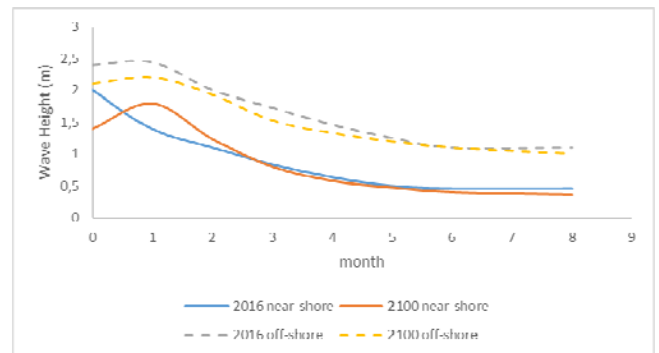


Figure 9. 2016 and 2100 wave heights at 2.5 degrees longitude (off-shore) and $\frac{1}{2}$ degree (near-shore).

2.7 Iceberg melting model

We used the iceberg melting model developed by White et al. (1980) with the calving model of Savage (1999) and a wave-erosion damping coefficient from Gladstone and Bigg (2001), to determine melting rate of icebergs, given wind speed, wave height, sea-surface temperature and ice fraction. These formulations are documented in the literature, but a brief description of how they are used is presented here.

Icebergs off Newfoundland and Labrador are exposed to three dominant modes of heat transfer (EL-Tahan et al., 1987). They are, in order of importance:

- 1 Convection/erosion caused by wave action, which causes ½ - 3/4 of all melting.
- 2 A by-product of wave erosion known as calving. Wave action causes a notch in the iceberg that eventually becomes large enough to break off due to the weight of the ice overhanging the notch. Calving causes approximately ¼ of all melting.
- 3 Convective heat transfer due to the motion of the iceberg relative to the surrounding water, caused by wind action and current variations with depth. The convective heat transfer accounts for about ¼ of all melting. The speed of the iceberg relative to the surrounding water is determined by a relation recommended by EL-Tahan and confirmed by Wanger(2017) of 0.017 of the wind speed.

Other factors influencing iceberg melting, such as solar radiation, buoyant convection caused by water density gradients, and convection on the air side of the iceberg are small enough to be overlooked (EL-Tahan et al., 1987).

The melting model results in a melting rate which can be numerically integrated over time. We use an explicit scheme for marching forward in time, with the iceberg dimensions of the previous time step for all calculations. This procedure requires a sufficiently small time step, determined by a trial-and-error process until the elapsed time to melt no longer changes significantly. 1 day was determined to be an appropriate time step for these calculations.

The iceberg was assumed to be of the “blocky” type, as described by Robe (1983), with equal length and width, and a height that is 0.7 times the side length. At the end of each time step, new mass and dimensions of the iceberg are calculated, after which a new time step is begun. When the mass of the iceberg reaches zero, the iceberg has melted and the iterations finish.

Icebergs are surrounded most of the year by frozen sea water of varying sea-ice fraction (ice area/total area), known as pack-ice or sea-ice (in contrast, icebergs are composed of frozen fresh-water from glacier termini). Sea-ice can have a significant effect on iceberg melting for two reasons: a) sea-ice lowers the height of waves b) sea-ice provides damping of the eroding effect of waves.

We used the equation given in Gladstone and Bigg (2001) for the damping coefficient damp of waves in sea-ice as a function of sea-ice fraction *icefrac*:

$$damp = 0.5 * (1 + \cos(\pi icefrac^3)) \quad [5]$$

The wave erosion velocity from White (1984) is multiplied by the damping coefficient. Please see the computer code presented in the appendix.

Eq (5) results in damping coefficients close to 1 below about 0.35 ice fraction, and damping coefficients close to zero for ice fractions greater than about 0.85.

We tested our model against the results of EL-Tahan et al. (1987) Case 2, for a very large 6.25×10^6

ton iceberg (1 ton is 1000 kg) melting in the Grand Banks, with SST = 3 C, ice fraction of zero, wind speed of 8 m/s and average wave height = 1.5 m. Figure 10 shows the accuracy of our model is reasonable.

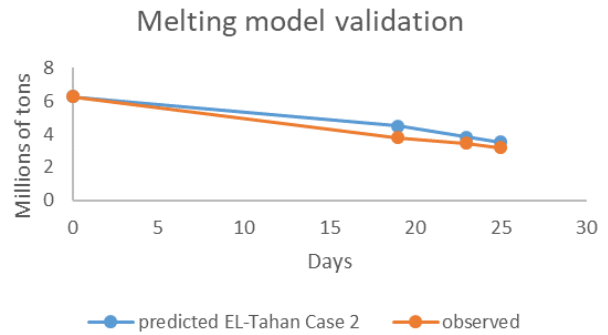


Figure 10. Predicted iceberg length using melting model, compared to observed length.

3 RESULTS

3.1 Environmental Variables

Applying the methods listed in the previous section yields the following correlations for environmental parameters, for years 2016 and 2100, as a function of month *m* from December to August, averaged in Labrador and Newfoundland waters out to 5 degrees of longitude off-shore. Month 0 is December, 1 is January, etc. These equations are necessary as inputs to the melting model as it incrementally marches forward in time in during numerical integration:

$$\begin{aligned} SST_{2016} (C) = & -0.002497 m^6 + 0.054923 m^5 - 0.444948 \\ & m^4 + 1.634709 m^3 - 2.419993 m^2 + 0.348767 m + \\ & 1.148874 \end{aligned} \quad [6]$$

$$\begin{aligned} SST_{2100} (C) = & -0.003336 m^6 + 0.074290 m^5 - 0.615148 \\ & m^4 + 2.360881 m^3 - 3.887948 m^2 + 1.000498 m + \\ & 3.279805 \end{aligned} \quad [7]$$

$$\begin{aligned} Wind\ Speed\ 2016 (m/s) = & 0.036246 m^3 - 0.412504 m^2 + \\ & 0.451308 m + 10.533232 \end{aligned} \quad [8]$$

$$\begin{aligned} Wind\ Speed\ 2100 (m/s) = & 0.002019 m^5 - 0.043250 m^4 + \\ & 0.356252 m^3 - 1.356886 m^2 + 1.430346 m + 9.687086 \end{aligned} \quad [9]$$

$$\begin{aligned} Ice\ Cover\ 2016 (\% \text{ ice}) = & -0.01 m^5 + 0.2859 m^4 - 2.183 m^3 \\ & + 1.2246 m^2 + 23.134 m + 12.601 \end{aligned} \quad [10]$$

$$\begin{aligned} Ice\ Cover\ 2100 (\% \text{ ice}) = & -0.0169 m^6 + 0.367 m^5 - 2.5824 \\ & m^4 + 5.2418 m^3 + 5.0516 m^2 - 5.0192 m + 11.056 \end{aligned} \quad [11]$$

$$\begin{aligned} Transit\ time\ 2016 (\text{days, where } m \text{ is the starting} \\ \text{month at } 60N) = & 1.6536 m^2 - 3.2164 m + 57.95 \end{aligned} \quad [12]$$

$$\frac{\text{Transit time 2100 (days, see note above)}}{3.9429 \text{ m} + 70.286} = 1.5714 \text{ m}^2 - [13]$$

The equations below for H^* and F^* apply to all months, for fetches up to about 5 degrees longitude off-shore in waters off Labrador and Newfoundland:

$$\frac{\text{Dimensionless wave height } H^* = -0.045376F^{*3} + 13.820094 F^{*2} - 344.731632 F^*}{[14]}$$

$$H^* = \frac{\text{fetch} \times \cos(1 - \text{ice fraction})}{\text{wave height}} [15]$$

$$\frac{\text{Dimensionless fetch } F^* = \left(9.8 \text{ fetch} \right)^{\frac{1}{2}} \times \cos(1 - \text{ice fraction})}{(wind speed)} [16]$$

3.2 Effect of environmental variables on melting

If an extremely large iceberg drifts from northern Labrador (60N) to the shipping lanes in Newfoundland (48N latitude), the iceberg will survive the journey with only partial melting. When the initial iceberg size is decreased in small increments, the final size of the iceberg at 48N decreases as well, but at some initial size the iceberg melts just after crossing 48N. We refer to this initial size as the Minimum Transit Size (MTS) – icebergs smaller than the MTS succumb to melting on their transit. We use MTS to quantify increased melting as well as to predict future iceberg numbers.

Figure 11 was generated by looping our melting model through decreasing iceberg sizes until melting was achieved. The figure shows the minimum transit size (MTS) from Labrador to Newfoundland in years 2100 and 2016, for transit along a typical iceberg path 2.5 degrees of longitude away from the shore. The figure shows a significant increase in maximum melting size, ranging from 48% in December to 20% in March.

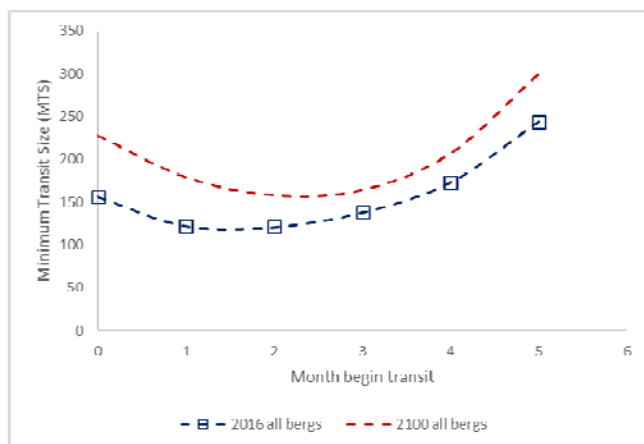


Figure 11. Iceberg smallest size that will not melt in transit from 60N to 48N for years 2100 and 2016

The effect of the greater melting on iceberg numbers reaching 48N can be estimated from Nalcor (2015), which recommends the equation below for

iceberg length probability of exceedance in waters off Labrador and Newfoundland:

$$\text{Percent exceedance} = 128.23 e^{-0.017L} [17]$$

where L is the length of the iceberg in meters.

The data used for Eq (17) were collected in 1983, and represent the best available information on iceberg sizes.

In order to estimate what the effect this increased melting might have on iceberg numbers drifting into the shipping lanes, we assume that size distribution in 2100 and 2016 will be similar to that encountered in 1983 (we are forced to make this assumption, due to unavailability of other reliable data). We reason that the percentage of icebergs of a given size surviving the journey from 60N to 48N latitude is the same as the probability of exceedance. Figure 12 shows the percentages of total icebergs at 60N that survive their journey to 48N, as a function of the month at 60N, for years 2016 and 2100. Year 2100 bergs will reach the shipping lanes 70 – 90 days later, assuming no groundings.

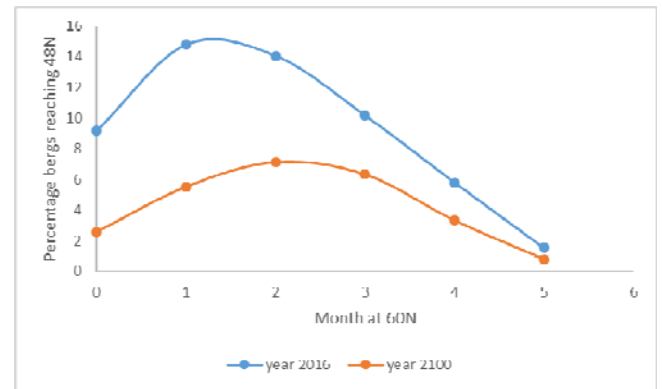


Figure 12. Percentage of icebergs in waters off Newfoundland that will not succumb to melting on their journey from 60N to 48N.

Figure 13 shows reductions in iceberg numbers ranging from 40%-50% for arrival dates between March and July, which is when the bulk of the icebergs exist below 48N. In August, when fewer or no icebergs exist below 48N latitude, our analysis indicates that iceberg numbers should be about the same in 2100 as 2016.

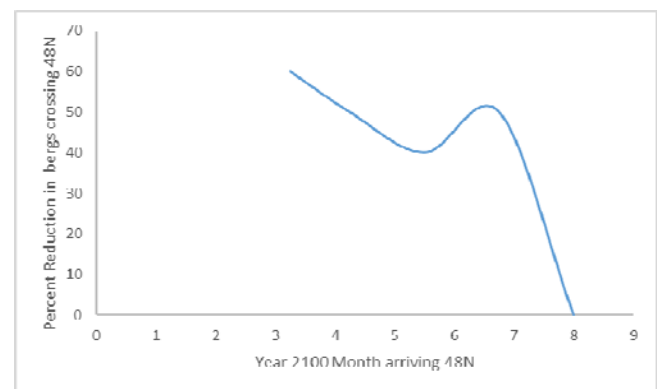


Figure 13. Reductions in iceberg numbers crossing into the shipping lanes, relative to year 2016.

Figure 14 shows the contribution to future melting of bergs following an average path, due to increased transit time, sea surface temperatures and reductions in sea-ice concentration. Sea surface temperature increases are seen to be the most important, followed by increased transit time and decreased sea ice. It is noted that a predicted decrease in wind speed does not by itself affect melting, although it is probably responsible for at least a portion of the decreased current speeds. The wind has a small direct effect on melting for two reasons: the wind speed changes are relatively small, and wind speed directly affects only forced convection between sea water and the iceberg – a component of the total heat transfer that is eclipsed by erosion due to wave action and calving.

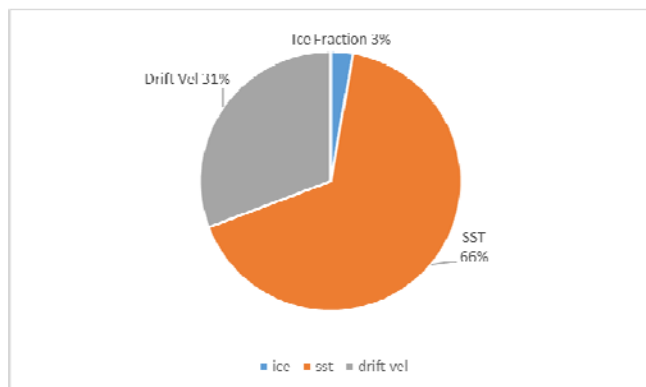


Figure 14.

4 CONCLUSIONS

Increases in sea surface temperature (SST), as well as decreases in sea-ice cover, wind and current velocities will have a marked effect on iceberg melting off Newfoundland and Labrador.

The minimum length for icebergs surviving their journey without succumbing to melting (MTS) increases significantly in year 2100, as compared to current MTS values. For example, icebergs at N Labrador in December of 2016 that are smaller than 156 m will melt before reaching 48N, but in year 2100 the length increases to 228 m.

Assuming future iceberg size distributions and iceberg numbers off Labrador that are the same as today, icebergs drifting into the NW Atlantic shipping lanes off Newfoundland are predicted to significantly decrease in numbers by year 2100. In March through July crossings into the shipping lanes (when most of the icebergs cross into the area) icebergs will experience roughly 50% reductions in numbers, as compared to the present. These findings are consistent with the range predicted by Han et al. (2015) using extrapolations of environmental parameters.

The increased melting rates are due to, in order of importance, increased sea-surface temperatures (responsible for 66% of the increase in the minimum transit size), decreasing current velocities (31%), and decreasing sea-ice cover (3%). Decreasing sea-ice tends to increase wave heights as well as accelerate the effects of wave erosion; however, for the areas

studied the wave height is predicted to decrease moderately in year 2100, by a maximum of about 10% in December.

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APPENDIX

VBA Code for predicting iceberg melting

```
'uses formulas from White and calving model from Savage
'inputs
Dim xl(300)
sst = 10.5      'sea surface temp degrees C
rhoice = 900    'density kg/m^3
kwater = 0.569  'thermal cond w/m-k
visc = 0.0018  'viscosity water kg/m-s
ws = 10#       'wind speed m/s
wht = 0.7      'wave ht in meters
rhowater = 1000 'water density kg/m^3
tstep = 0.5    'time step in days
vr = ws * 0.017 'iceberg speed rel to water, per el-
tahan
```

```
deltaT = sst + 1.8 'delta T as SST minus melting
point suppressed by salt
hfg = 334          'latent heat of fusion ice in J/gram
tau = 7           'wave period in seconds
le = 120          'm length berg
xl(0) = le        'initialize iceberg length array
ruff = 0.02       'berg roughness in meters
erol = 0          'initialize erosion due to wavemaking
volume = le ^ 3   'initial volume
kvisc = 0.000018  'kinematic visc of water m^2/s
pr = 0.0109 * sst ^ 2 - 0.4922 * sst + 13.289 'curve
fit from white data.. for -1<= T<= 12

Open "berg" For Output As #1 'open output file

For i = 1 To (20 / tstep) 'loop
** convective losses **
Re = vr * xl(i - 1) / kvisc 'Reynolds number
Nu = 0.055 * (Re) ^ 0.8 * (pr) ^ 0.4 'Nusselt number
h = Nu * kwater / xl(i - 1) 'heat/mass
transfer coefficient
q = h * deltaT * asurf 'heat flow in watts to berg
mlossConv = q / hfg * 3600 * 24 / 1000 * tstep 'mass
loss by convection in kg/tstep
vlossconv = mlossConv / rhoice 'm^3 lost per
tstep to convection
llossconv = Nu * deltaT * kwater / (xl(i - 1) * hfg *
1000 * rhoice) * 3600 * 24 * tstep
'length loss conv (m)
** wave erosion losses **
'recession vel at perimeter in m/day
velwave = 0.000146 * (ruff / wht) ^ 0.2 * wht *
deltaT / tau * 3600 * 24
erolthis = velwave * tstep 'wave erosion this
time step (meter)

'for calving
erol = erolthis + erol 'wave erosion length
accumulated since last calve
tslab = 0.196 * xl(i - 1) 'thickness of slab (m)
over the wave erosion, at calving
failL = 0.33 * (37.5 * wht + tslab ^ 2) ^ 0.5 'notch
length at which eroded area breaks under own wt
'total volume loss
lcalv = 0.3 * erolthis
xl(i) = xl(i - 1) - llossconv - erolthis - lcalv
10 Print #1, i * tstep, xl(i)
lcalv = 0
Next i
Close #1
```