
Report

Iceberg Flux and Climate Change

FOR THE CANADIAN ICE SERVICE
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Canadian Ice Service
Environment Canada
373 Sussex Drive, Block E
Ottawa, ON
K1A 0H3
Scientific Authority:
Tom Carrieres

Submitted by:

Dr. S. E. Bruneau
CBERG Consulting Services
13 Darcy St., St. John's NL, Canada, A1A 5B9
Ph 709 722-6542



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PREAMBLE

This report details the work by Dr. Stephen E. Bruneau, Assistant Professor of Civil Engineering at Memorial University. Dr. Bruneau in his capacity as a contracting consultant entered into a Short Form Service Contract with AES Ice Centre, Tom Carriers Scientific Authority. The work was carried out between June of 2007 (earliest field component) and March of 2008 (final analytical work). Dr Bruneau wishes to acknowledge support from colleagues Dr. Greg Crocker and Mr Tom Carriers and also the contributions of Memorial students Mr Eugene Manning, Mr Evan Martin and Mr Kris Rogers for their technical assistance.

BACKGROUND

The Canadian Ice Service (CIS) provides sea ice and iceberg information to governmental and industrial users on Canada's east coast and in the Canadian Arctic. Hydrocarbon exploration and development activities on the Grand Banks of Newfoundland have resulted in an increased demand for iceberg information in this region. In response to this user requirement, and to further meet its mandate of environmental protection and the safety of lives at sea, the CIS is actively developing improved iceberg products and services.

The CIS iceberg drift and deterioration model is used operationally to forecast and now-cast iceberg positions. It can also be used to investigate iceberg climatology. It is generally accepted that warming and other changes to the global climate system will continue through the next several decades. Changes to air and sea temperatures, currents, wind fields, and storm frequency, severity and tracking will all act to change the drift patterns of icebergs. The recent dearth of icebergs near to shore along Newfoundland's northeast coast may be evidence that this is already happening.

It is not presently known what the most important factors will be in controlling changes to iceberg drift patterns, how drift patterns might be changed, and how the flux of icebergs to the hydrocarbon developments on the northern Grand Banks will be affected. In this study the CIS iceberg drift and deterioration model will be used to conduct parametric studies of the effects of plausible changes to met-ocean conditions on the drift patterns and flux of icebergs from Davis Strait to the northeast coast of Newfoundland and the northern Grand Banks.

ICEBERG MODEL INSTALLATION AND CHECKS

This section of the report describes action items associated with installation, checking and the configuration of the model to facilitate efficient parametric investigations of iceberg flux and climate change. Specifically described are:

1. model implementation and checks for validation of version correctness
2. model operability for the purposes of studying *Iceberg Flux and Climate Change*
3. model input versus output statistical analysis for the purpose of prioritizing input parameters in the study of *Iceberg Flux and Climate Change*

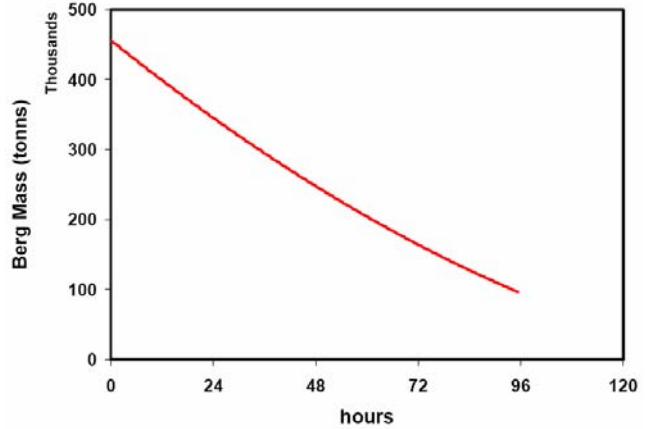
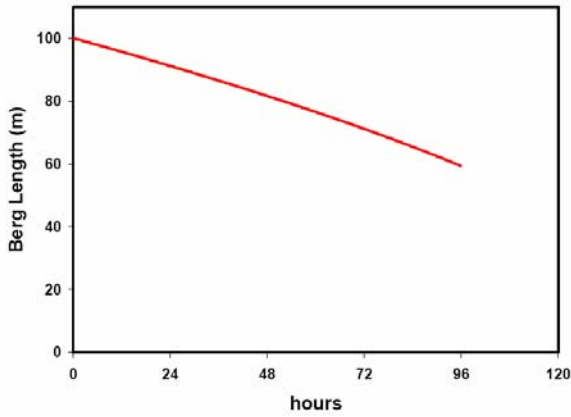
Model Implementation

The CIS iceberg model called *localberg* was obtained by the consultant through the procurement of a “Single System Licence For Local Iceberg Drift Software” agreement with a third party - the National Research Council, Canada (NRC). For proprietary reasons the version provided for evaluation was of a non-readable executable form and therefore could only be run exclusively as-is. Subsequent to the award of this contract an important publication became available from those credited for the CIS-NRC Local Iceberg Drift Model. The work is entitled “An Operational Iceberg Deterioration Model” (Kubat et al., ISOPE 2007), and in combination with an earlier publication “Determination of Iceberg Draft, Mass and Cross-Sectional Areas” (Barker et al ISOPE 2004) most of the relevant physics for both the drift and the deterioration components of *localberg* are explained.

Kubat et al (2007) describes the formulation for the iceberg deterioration component of *localberg* exclusively and importantly, the paper describes output sensitivity to certain key input parameters. One test case is described for which an aggressive melting scenario is modelled and several but not all input parameters are listed. To validate the version of *localberg* in hand this singular published test case was replicated for comparison. The test case from Kubat et al, 2007 features the following input data:

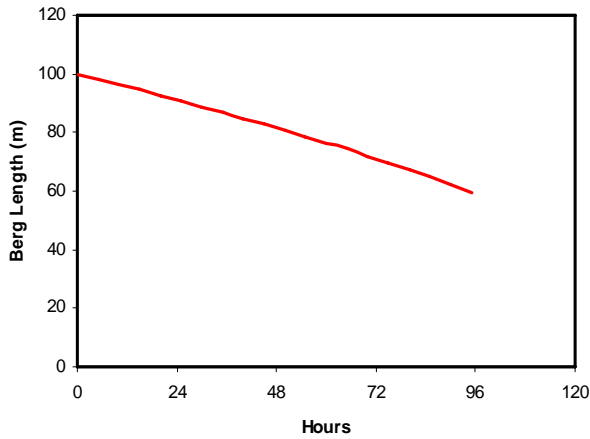
Kubat et al: Test Case in ISOPE 2007		
Iceberg waterline length	100	m
Sea water temp	11.9	C
Duration of run	4	days
Wind, wave & current deltas	none	
Wave height	2.1	m
Wave period	8	s
Wind Velocity	0	m/s
Current (velocity)	0.5	m/s

The resulting decrease in waterline length and mass were plotted versus time. Results showed a length decrease from 100 to 60 m and a mass reduction of 87% after 4 days.

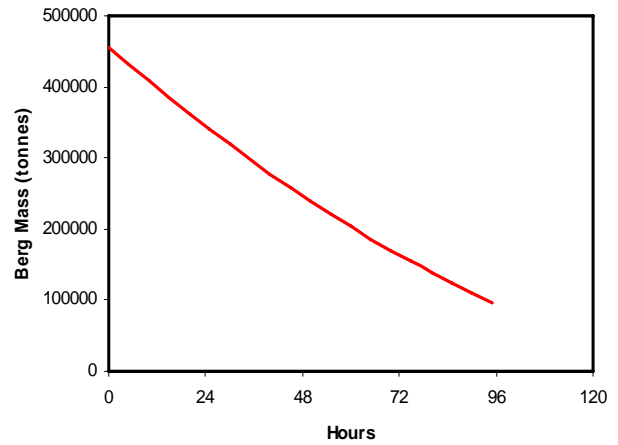


Utilizing the same input values as listed above and otherwise relying on the default data in the sample input parameter file, the following results were obtained by this author (complete input listing provided below):

Iceberg waterline Length Decrease over 4 Days



Iceberg Mass Loss over 4 days



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 CBERG Consulting Services
 under licence from NRC-CHC.

Model Parameters

Run Parameters	Initial Iceberg Variables	Environmental Forcing	Properties
userNsteps: 3390	userBergLength: 100.00	userWaterTemp: 11.900	userCdwat: 1.3000
userDelt: 120.000	userLong: 55.000000	userWaveHeight: 2.100	userCdair: 1.9000
userPrintFreq: 150	userLat: 50.000000	userWavePeriod: 8.000	userRhoice: 910.000
	userU: 0.0000	userInitUcurrent: 0.5000	userRhoair: 1.3000
	userV: 0.0000	userInitVcurrent: 0.5000	userRhowat: 1030.000
	userTabularGeometry: 0	userInitUwind: 0.0000	userKwater: 0.562000
	userKeelSailInput: 1	userInitVwind: 0.0000	userKair: 0.024100
	userKeelDepth: 70.000		userNuwater: 1.7900E-06
	userSailHeight: 10.000		userNuair: 1.3200E-05
			userLatentHeat: 3.3400E+05
			userAlbedo: 0.7000

The resulting output depicted above compares favourably to the output described and plotted in ISOPE. The deterioration clearly follows the same trends and is similar in magnitude; however, the mass reduction recorded by the test case in Kubat et al indicated an 87% decrease whereas the results computed here were just under 80%. The differences may be attributed to invalid assumptions by this author of those input parameters that are not provided in the ISOPE paper. None-the-less it is judged that this test sufficiently proves that the executable model obtained from the NRC is one and the same as that in Kubat et al, and, that it is functioning as intended.

Sensitivity studies have been carried out on the operational CIS model and are described in Kubat et al 2007. They were intended to guide in the operational use of the model. Parameters tested were water temperature, iceberg size (waterline length), wind and current velocities and wave height.

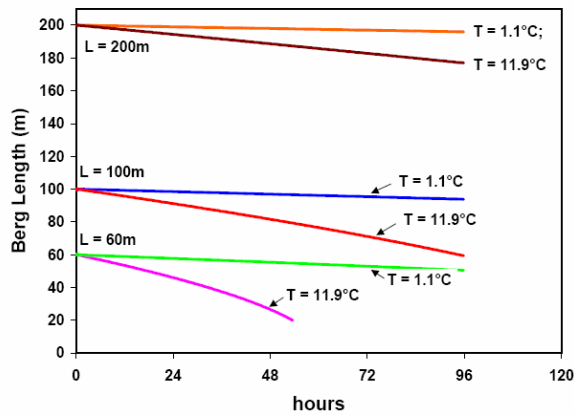


Fig.3a The influence of water temperature, T and iceberg L on iceberg deterioration – waterline length

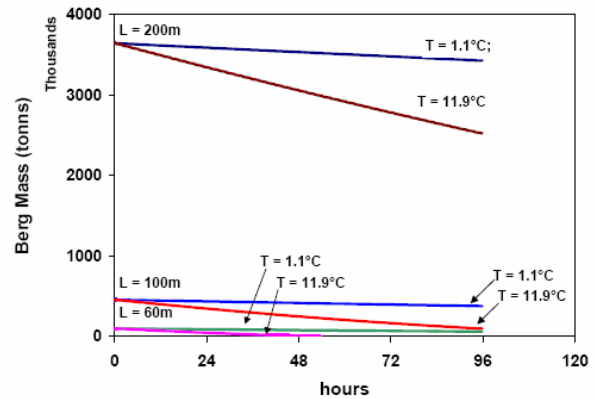


Fig.3b The influence of water temperature, T and iceberg L on iceberg deterioration - mass

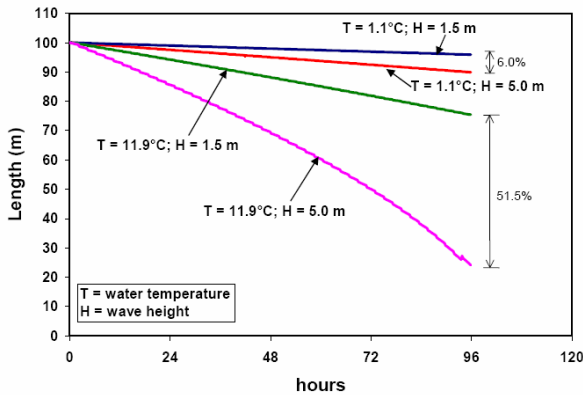


Fig.4a Effect of wave height, H , on iceberg waterline length

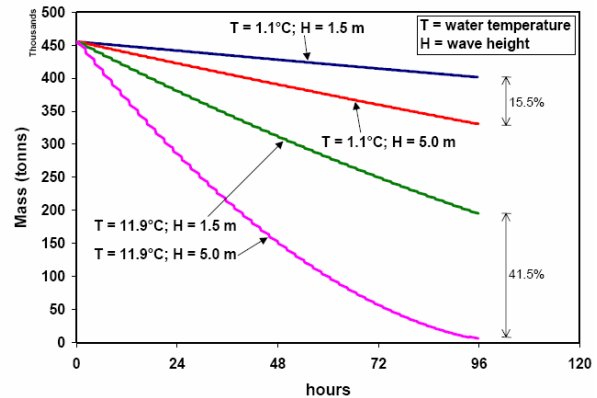


Fig.4b Effect of wave height, H , on iceberg mass loss

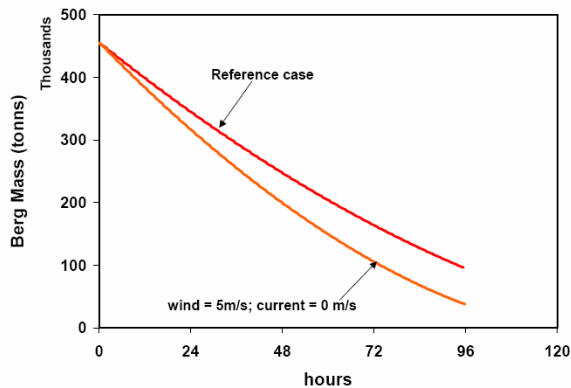


Figure 5: The influence of wind velocity on iceberg deterioration.

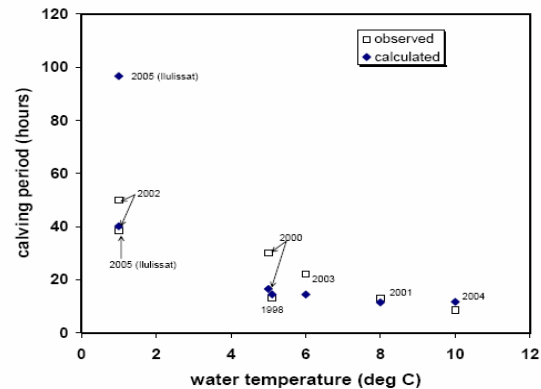


Fig. 6: Observed and calculated iceberg calving intervals.

The results indicated that wave height and water temperature were the most significant independent variables in the model when tested over a natural range of values. Other parameters affected decomposition noticeably but with less severity. Calving intervals were also shown to match reasonably well with field observations.

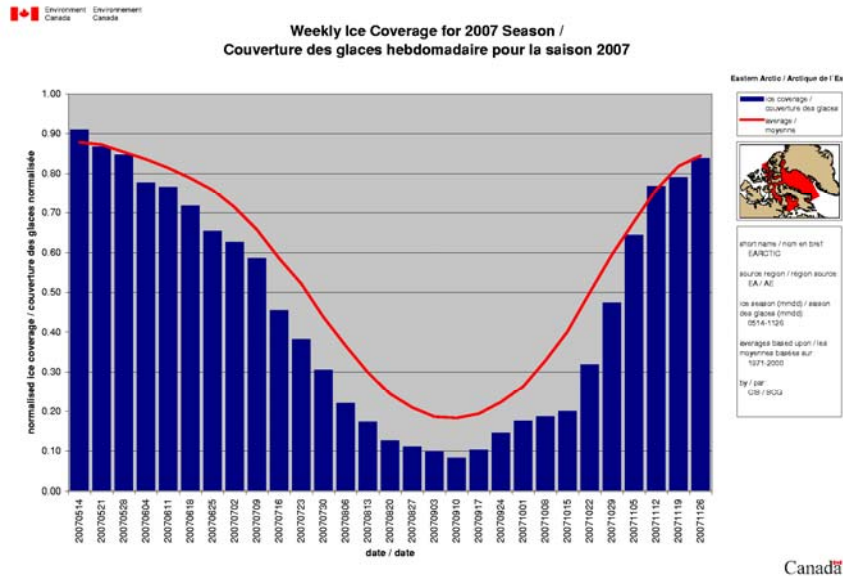
Extension of Sensitivity Studies

It is estimated that Greenland produces more than 100 billion tones of iceberg ice annually and that only 5% of this or about 2000 bergs make it through the Davis Strait each year. This implies that the vast majority of icebergs melt entirely within Baffin Bay or adjacent waters. This melting may not occur in a single season but can span several if the iceberg is unable to exit to the south into ice free waters.

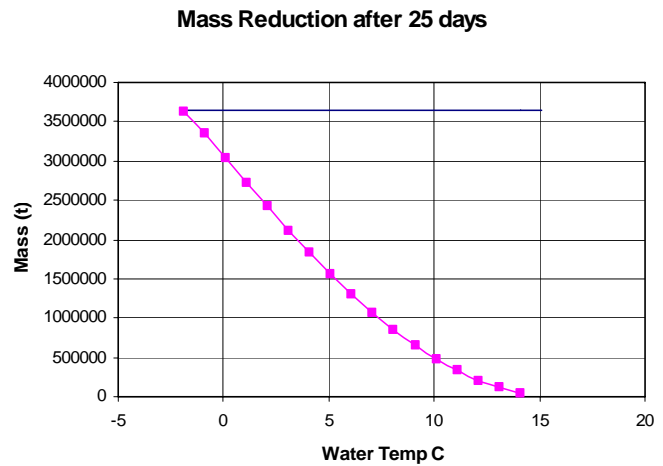
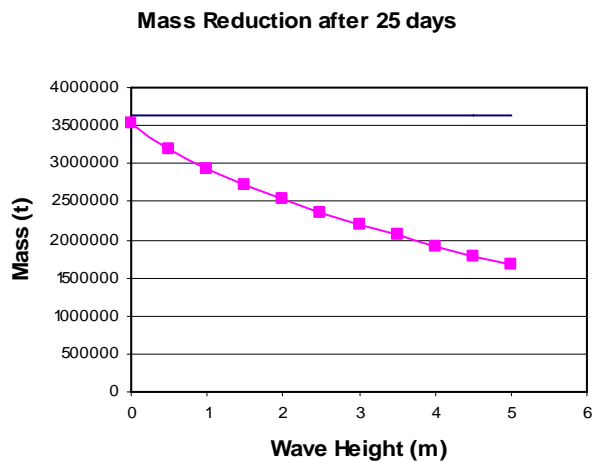
As will be discussed later in this report it is well established that icebergs do not melt or break up appreciably when locked in sea ice. Sea ice may convey bergs but water temperatures are usually below zero, air temperatures are usually below melting point and wave action is curtailed entirely. Thus icebergs are preserved and transported in sea ice – but not melted. The plot below indicates the average weekly ice coverage of Baffin Bay and also shows the anomalous histogram for the 2007 season.

Of note is the extended duration of the ice “free” (25% for this example) period from approximately 7 weeks in an average year to approximately 11 weeks for the 2007 season. Though this change in ice cover is relatively small when stretched out over the entire sea ice year (less than 10% change), it represents a whopping 50% increase in open water exposure to icebergs freed in that period. This sensitivity is illustrated by the following hypothetical deterioration cases as computed using the executable *localberg* model: If the average open water temperatures of Baffin Bay were 2C and wave height were fixed at 1.5 m with no wind or appreciable currents then an iceberg with a waterline length of 200m and mass of 3.6 million tonnes would take almost 20 weeks to vanish according to the CIS model. Raising temperatures to 4C reduces this to 11

weeks. A smaller berg at 100m and 450 kt in the same oceanic conditions would vanish in a little over 5 weeks in 2C water a mere 23 days in 4C water.



Travelling at 10 km/day south it takes 300 days to move from Baffin Bay to the Grand Banks. A 200 m berg would not survive this trip in water temperatures of zero degrees in very slight seas. Further support for this trend results from a series of *localberg* runs plotted below illustrating the deterioration as a function of wave height and water temperature. It is apparent then that the model supports the notion whereby the presence and extent of mobile sea ice from the northern reaches of Baffin Bay to North East Coast of Newfoundland is a key factor in ensuring iceberg survival.



Localberg must treat sea ice indirectly through inference in the environmental parameter states. Thus later sections of this report will attempt to describe the capacity of *localberg* to capture the range and type of parametric input necessary to capture sea ice effects.

Model Operability for This Study

The attributes of the computer model *localberg* are understood by the author to be those listed in the following table

environment	DOS
program platform	Fortran
data entry	user defined text file
data output	static text file
result	deterministic time series
integration environment	unknown
simulation procedure	batch send or manual

Within the DOS prompt window the executable runs in one of three modes:

1. the model alone by single line command without user defined input (default parameter values used) and with text line output to screen;
2. with a user defined input parameter file and screen output, or,
3. with user defined input and an output log file which is a soft print of the screen output.

It has been learned through personal communication with environmental data specialist Dr. Ken Snelgrove at Memorial, that weather forecasting, a scientific pursuit of many thousands of highly qualified people, make use of very similar modeling approaches to that described above for *localberg*. Typically forecasts are developed through a weighted averaging process in which models of various description and functionality are orchestrated in an ensemble approach to give the most likely probable outcome scenario. Exotic graphical interfaces and dynamic plotting are often carried out separately – harvesting data from many sources and putting them into an intelligible format for meteorologists and the public. It is assumed by this author that this model is likewise used by the Canadian Ice Services to fulfill its mandate by providing daily iceberg distribution charts for the East Coast. And in this way it thus appears that the model operability is quite satisfactory.

In this study, the CIS iceberg drift and deterioration model is to be used to conduct parametric studies of the effects of plausible changes in climate on the drift and flux of icebergs from the David Strait to the Northeast Coast of Newfoundland and the Northern Grand Banks. Noting that climate in this sense is the statistical representation of all meteorological and oceanographic states over an extended period of time, it can be said to have changed only when a statistically significant number of events or period of time has passed and been recorded so that trends may be gleaned from the data with some confidence. To validate the hypothesis of ‘change’ these trends must also demonstrate that they are in fact deviating from prior states of flux and intensity assumed to be a part of the previous climatic regime. These changes to the statistics which we call climate can only be applied to weather forecast (or iceberg forecast)

models in a probabilistic way, unless very high numbers of deterministic simulations are executed so as to achieve the desired shift. Through the intricacies of the physics involved and the inevitable correlation of some input data parameters individual model tests have no statistical when studying climatic variation.

This poses a challenge for the use of the *localberg* coding of the CIS drift and deterioration strategies, as it has been developed to a large extent to operate in a deterministic manner.

Localberg Code Experiment and ANOVA

The study of the affects of parameters (input) on iceberg drift and deterioration (output) as represented by *localberg*, is limited to an experimental execution procedure and subsequent interpretation using the statistical tool called analysis of variance (ANOVA). The results of an ANOVA allow the user to see how the output is determined by the inputs when several dynamical and potentially correlated or competing phenomena are involved. In this case the model code is not known but the underlying physics have been explained and there is reason to proceed with an ANOVA due to the high number of variables involved. The following is a summary of procedure and results as the details are contained in other work under separate cover:

The ANOVA requires the user to identify parameters judged to be of importance, or at least assists in identifying those with a lack thereof. Two output values were selected to give an indication of the two primary outcomes of the *localberg* model: (1) deterioration, for which waterline length was selected, and (2) drift, for which net latitude traversed south was used. The input parameters used for this study are listed below as are representative values of somewhat low and high magnitude for each. A third, mid range value, has also been used in this experiment to test parameter importance for non-linearity – a result considered too speculative and therefore not reported in this work:

ANOVA Parameter IDs, Units and Range

ID	Parameter	Units	Low	High
A	Iceberg Length	m	100	250
B	Water Temperature	C	-1.5	12
C	Wind Wave Height	m	0.5	10
D	Wind Wave Period	s	2	12
E	Northerly Water Current	m/s	0	-0.5
F	Northerly Wind Velocity	m/s	0	-40
G	Water Density	kg/m ³	1000	1030

Note	Individual Parameters	7
	Paired Parameters	21
	Parametric Groups of 3	35
	# Parameters Tested	63

Results for the ANOVA investigating the latitude traversed south using the *localberg* executable model are listed below:

ANOVA results for - DRIFT

ID	Parameter	Percentage Contribution	RANK
F	Northerly Wind Velocity	58	1
C	Wind Wave Height	15	2
CF	WaveHt&Wind	15	3
E	Northerly Water Current	5	4
A	Iceberg Waterline Length	1	5
AF	Length&Wind	1	6
AC	Length&WaveHt	1	7

97% out of 63

Note: Shown are the only parameters demonstrating statistical significance

Importantly, these results are based on input ranges and other assumptions of default conditions which may, or may not be ideal for this test. Notwithstanding this it is apparent that the Northerly wind dominates iceberg drift, amongst a field of many parameters. The correlation of wind to wave height, another significant drift factor, may also explain the similarity of magnitude between the combined parameter and wave height alone – though this may be coincidence. Water currents as defined in the input table have a relatively low contribution to drift, a mere 5% - a full order of magnitude less than wind. None of the other parameters or combinations thereof demonstrated appreciable influence on the *localberg* drift.

Results for the ANOVA investigating deterioration of waterline length using the *localberg* executable model are listed below:

ANOVA results for - DETERIORATION

ID	Parameter	Percentage Contribution	RANK
B	Water Temperature	27	1
C	Wind Wave Height	17	2
BC	Temp&WaveHt	16	3
A	Waterline Length	11	4
AB	Length&Temp	10	5
AC	Length&WaveHt	7	6

89% out of 63

Note: Shown are the only parameters demonstrating statistical significance

Again these results are based on input ranges and other assumptions of default conditions which may, or may not be ideal for this test. Caution should be exercised when interpreting results. The pattern that appears from this second test indicates water temperature, wave height and iceberg size all have significant contributing roles in the *localberg* model. These three factors and combinations of them are alone responsible for iceberg deterioration. Whether these parameters are sufficient or preferred for representing the presence or persistence of sea ice must be determined.

In this simplistic analysis characteristic environmental driving parameters that have been shown to play a significant role in the output of *localberg* are wind, wave height, water temperature and to a lesser extent currents. Iceberg size also influences drift and deterioration rates. It cannot be assumed from this analysis that all other parameters are insignificant because many were not tested as this requires an exponentially increasing number of trials to execute an ANOVA with the addition of each new parameter. It is recommended that the healthy exercise of extending this study to other input parameters and for a consensus set of input ranges be undertaken. In this way, model developers and users may eliminate efforts in the pursuit of parameters for which there is little model benefit, perhaps withdrawing them from the list of user-defined input. Additionally, a focus may be placed on the better understanding the subtleties of, and correlation between, the important ones.

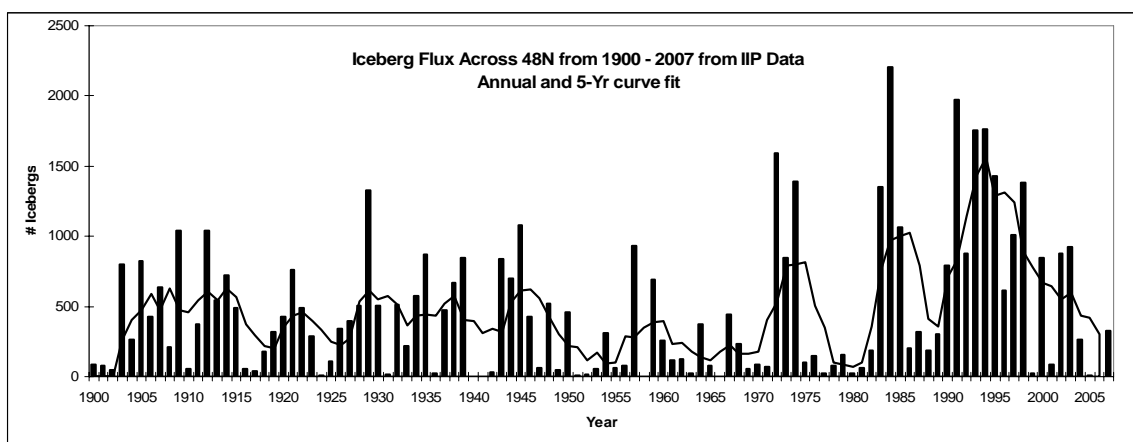
ICEBERG FLUX PARAMETRIC STUDY

The climate of icebergs in the Northern hemisphere and in particular on the Atlantic side may be characterized in many ways: production rates from glaciers, size and shape distributions, spatial and temporal frequencies even physical characteristics. For the interests at hand, there are a few iceberg climate descriptors that have an overriding importance; and in particular, one for which a significant data archive exists – that is iceberg flux across low latitudes. Traditionally the 48N latitude mark has been used as it marks entry from the North into the Grand Banks and Flemish cap areas where significant oil and gas exploration and production take place and below which huge volumes of commercial traffic and fishing exist.

In this study annual iceberg flux below 48N (Iflux) is the climatic descriptor under scrutiny. Changes to it that result from speculative shifts in environmental driving forces is, in part, the objective of this work. A brief investigation of the historic values of IFlux has been carried out so that a basis may be known from which change can be detected.

The international Ice patrol provides a monthly and annual summary of iceberg flux across 48N from the year 1900 to present. This data is available on the IIP website. Many conditions and comments may be made concerning the accuracy and precision of values over time as there have been changes in technologies, reporting procedures, modeling, spatial and temporal coverage and other. Notwithstanding these issues, it is exceptionally fortunate to have access to this hard-found data and it is the view of the author that the error which may be present in the data record is somewhat nullified by the consistency of it, and the natural variability of the statistic under consideration.

Iceberg flux for the years 1900 – 2007 are presented in the plot below:



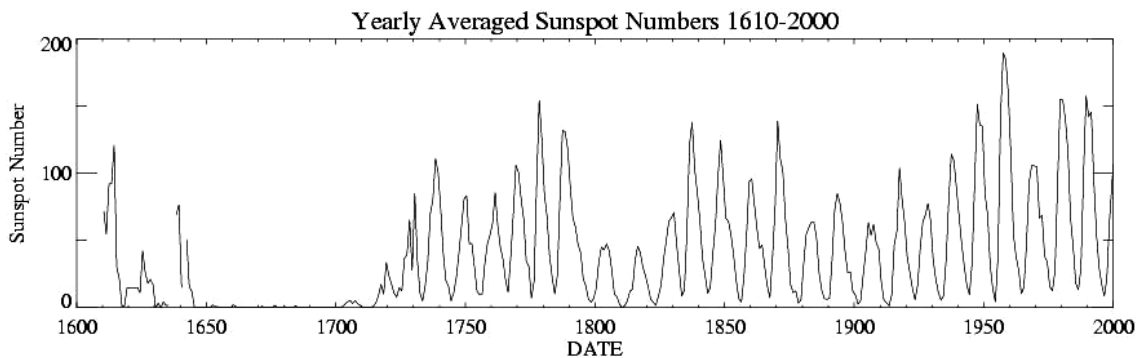
A five year running average of IFlux is also plotted and can be seen in the background. Though masked somewhat by the noisy annual scatter, an obvious periodicity is present in the data. The cycling is roughly fixed about two frequencies, the first and most

prevalent has a period of between 10 and 11 years as can be gleaned from counting the peaks over the timescale of the plot. The second more speculative frequency is longer term with an apparent low through the 50s and 60s and highs in the 80s and 90s. A corresponding high in the data of the early century is not obvious though it can be said that fewer people with more primitive tools for reporting these things persisted at that time.

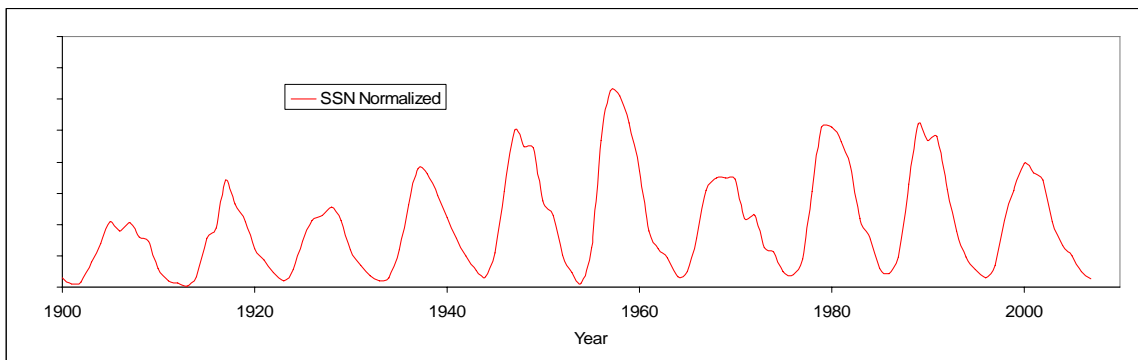
In any event, prior experience of the author led to the hypothesis that the decade-like fluctuation may be linked to the well recorded cycle of solar activity of the same frequency or perhaps may be linked to the North Atlantic Oscillation (NAO) – a significant periodic climatic phenomenon of the North Atlantic Ocean.

Solar Influence

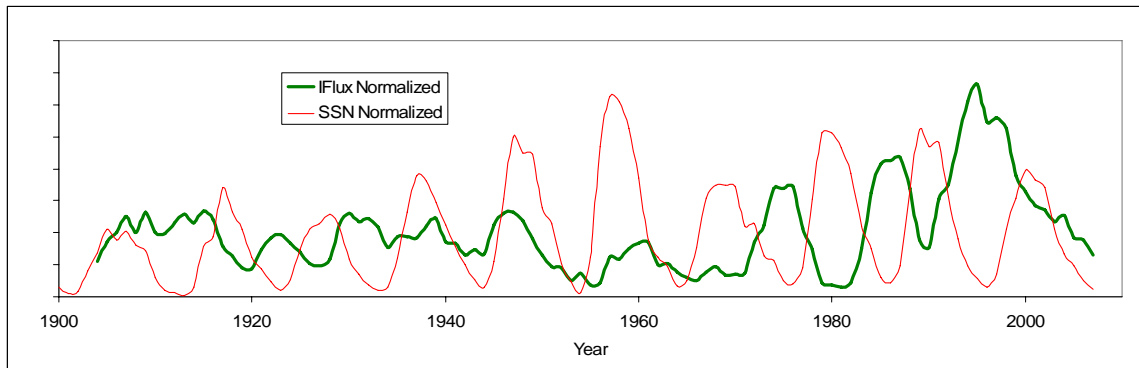
It has long been speculated that solar output quantified by sunspot activity influences annual weather intensity and patterns. Sunspot number compiled by the United States National Ocean and Atmospheric Administration (NOAA) are plotted below for the period from 1610 to 2000.



When this data is truncated for the period from 1900 and beyond, and normalized by division of the mean the plot looks like this:

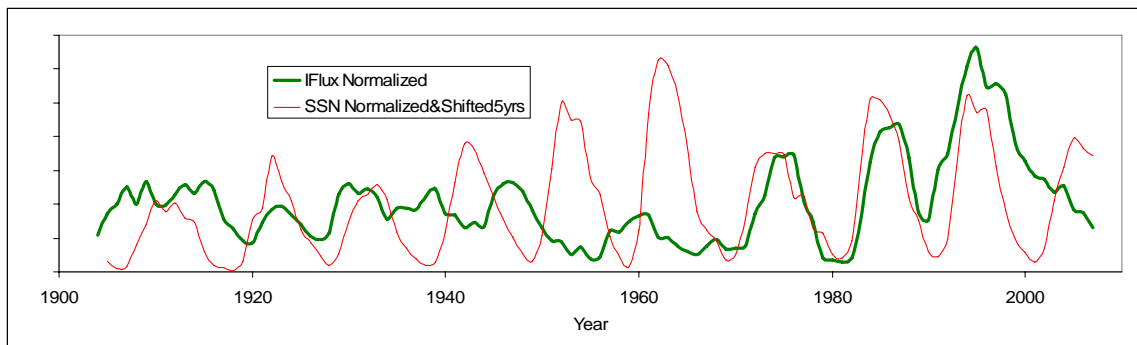
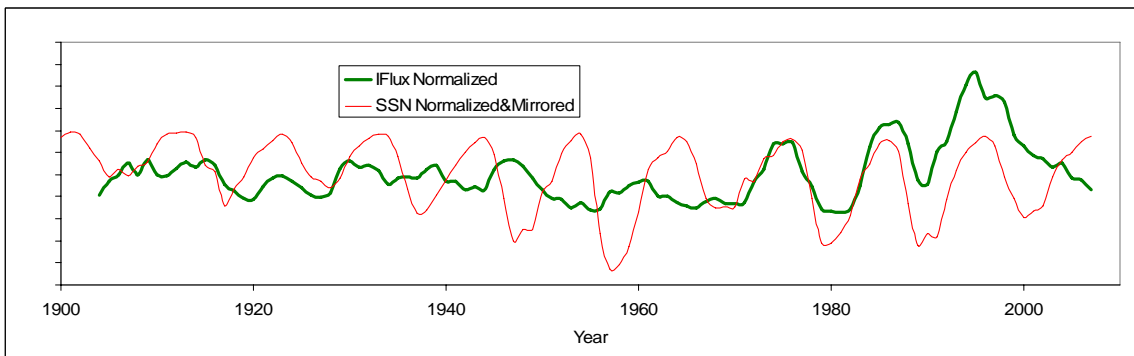


Superimposing the normalized IIP Iceberg Flux Data (IFlux) and the normalized NOAA Sunspot Number (SSN) the following plot results:



A few things are apparent in this graph – the periodicity of these two phenomena are remarkably similar, the relationship appears to be either an inverse or lagging type, and the period of highest solar intensity corresponds to the period of fewest icebergs and pattern disruption in the 50s and 60s.

The next two graphs show this same data with alternate plotting scenarios, the first with the solar activity curve mirrored about the temporal axis, and the second with the solar number merely shifted five years forward in time.

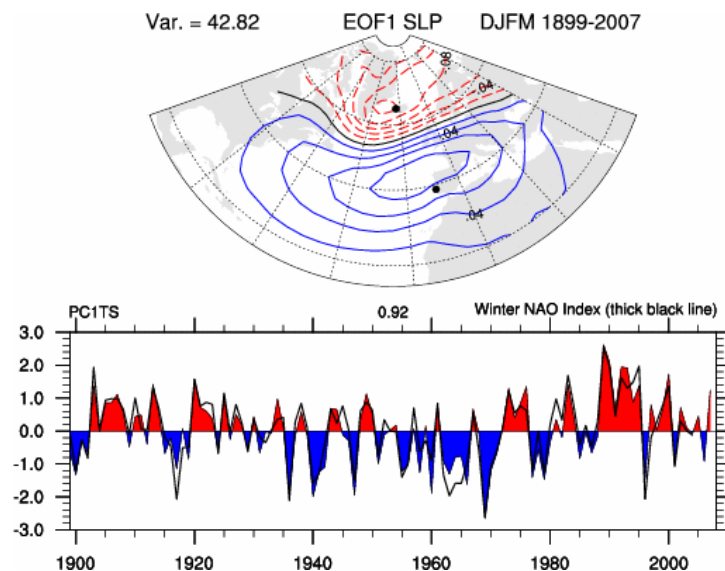


A Fourier and correlation analysis of these phenomena is being undertaken by the Author to ascertain more precisely the nature of the correlation, and suffice to say that the linkage is compelling if in fact the scientific validity holds.

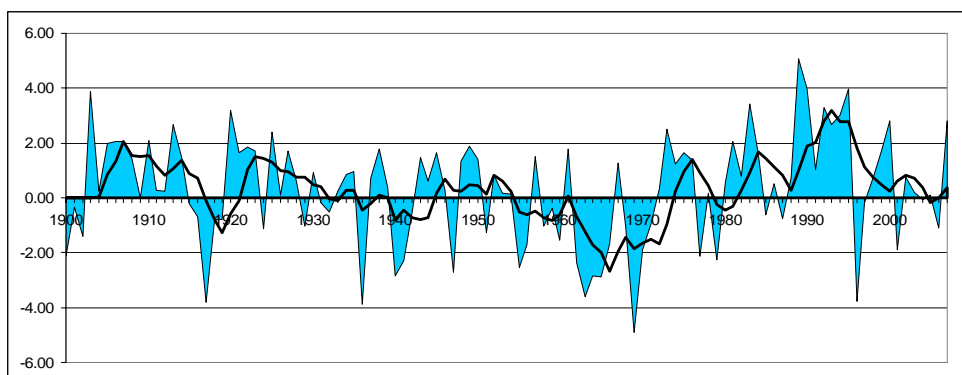
NAO Influence

The North Atlantic oscillation (NAO) is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of sea-level pressure between the Icelandic Low and the Azores high. There are several indices for measuring this, for instance, the winter (December through March) index is based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland and has accurate records available since 1864. It is now becoming a broadly publicized and scrutinized phenomenon and is commonly linked to interannual variations in met-ocean conditions and related dependants. The action of the NAO is through an east-west rocking motion of the Icelandic Low and the Azores high, and in this way the NAO controls the strength and direction of westerly winds and storm tracks across the North Atlantic. It is highly correlated with the similarly coined Arctic Oscillation, as it is a part of the same larger scale climatic phenomena.

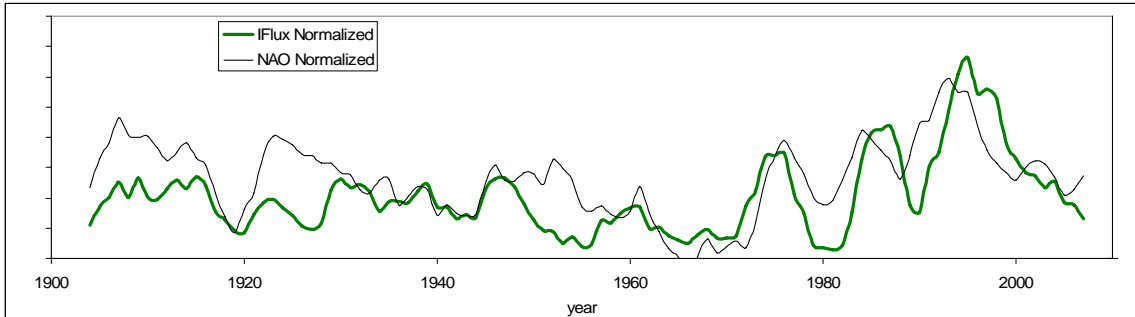
Below is a plot of the NAO for the period of 1900 to 2007 as provided through the United States National Centre for Atmospheric Research.



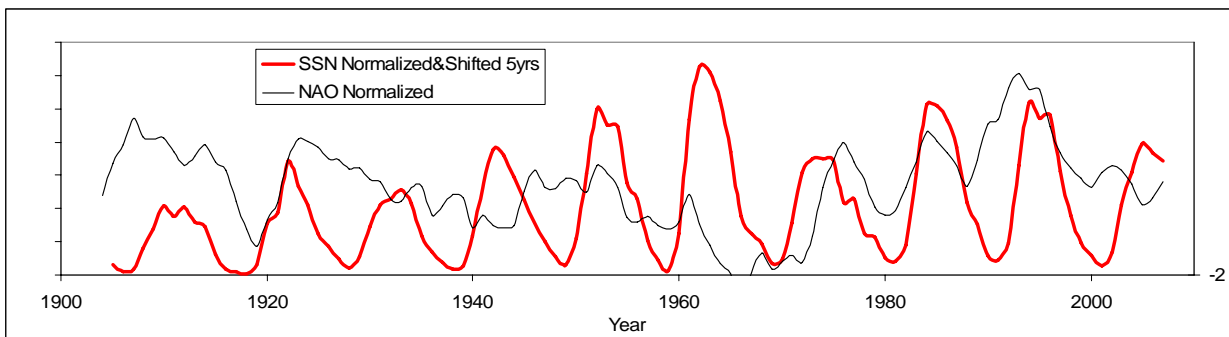
An obvious periodicity of a similar timescale to the SSN and IFlux is apparent here also with a general decline in the index over the period of the 50s and 60s. A five year running average was developed from this data and is plotted in the background below:



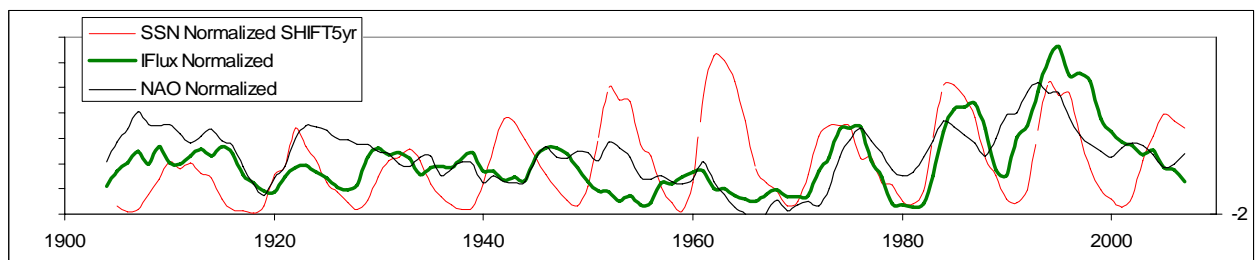
The NAO data was then normalized and superimposed on the IFlux data for the same period with the following result:



The two plots of normalized and 5-year averaged data for iceberg flux and the North Atlantic Oscillation can be mistaken for each other if it were not for some phase irregularities. The measure of NAO must be a very strong indicator of iceberg flux as the possibility for repetition of measured data is not present given the independent and unrelated manner in which the two parameters are measured. The value of the NAO for predicting future iceberg trends remains to be seen as it too may also be characterized by equivalent or even greater uncertainties. Regardless, the two are inextricably paired in one way or another and the research pertaining to the future state of one should be kept in watch by those engaged in the other. By inference the relationship of the NAO to SSN is assumed and for the interests of completeness is graphically presented below:



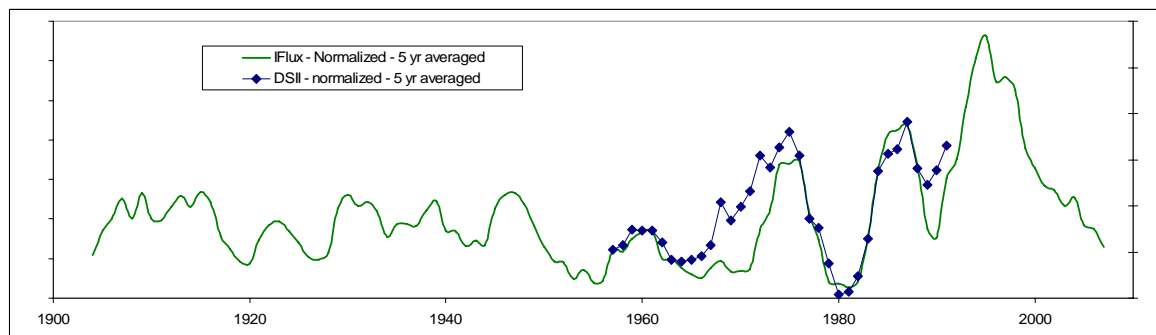
In conclusion the three-way interdependency of the parameters may be inferred from the following plot while bearing in mind the single unquestionable fact that solar activity is, in no conceivable way, influenced by icebergs, the Atlantic Ocean or, in all probability, the presence of the earth itself.



Sea Ice Influence

Nor does the sun push icebergs appreciably. The North Atlantic Oscillation is itself an index of pressure differentials which alone would have unimaginably small direct influence on iceberg flux. The point being that it is not the direct influence of these elements at play, but the local environmental driving forces that are inextricably linked to them, which explains the phenomenological linkages.

Evidence from a multitude of literary sources (Marko et al. 1994, Peterson et al 2000 for example) indicates a very high, direct correlation between sea ice seasonal and interannual changes and iceberg flux below 48N. The main features, according to Marko et al. (1994) of observed variation in the numbers of icebergs reaching 48N can be explained *“in terms of the sea ice conditions whereby the critical role of the ice is to assure the survival, to more southerly latitudes, of a very small fraction of the iceberg population created each year at regional glacier termini”*. Also, Marko noted, the very close empirical connections among the Spring Labrador ice extent, the regional surface temperature and pressure fields, and the spatial extent of sea ice in David Strait in January suggest that the David Strait Ice Index (DSII) is representative of the regional climate. This being said the DSII data for the period between 1953 and 1991 was extracted directly from the Marko paper and plotted against historic IIP data with the following result:



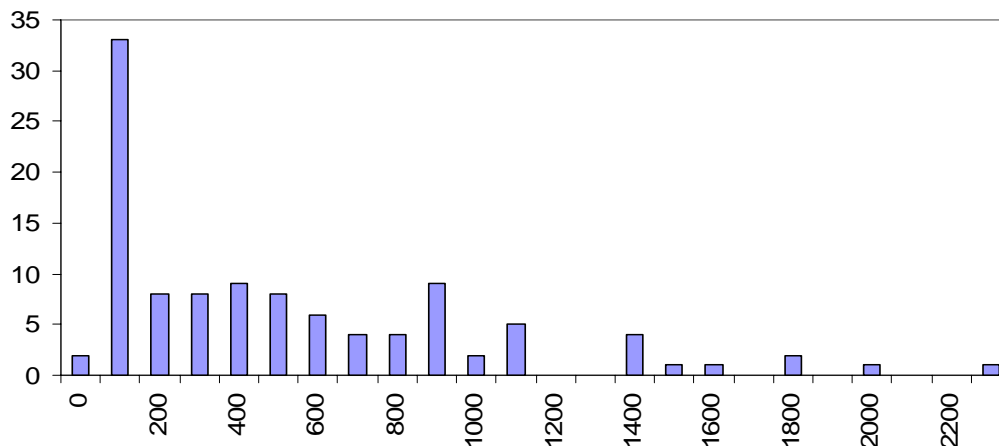
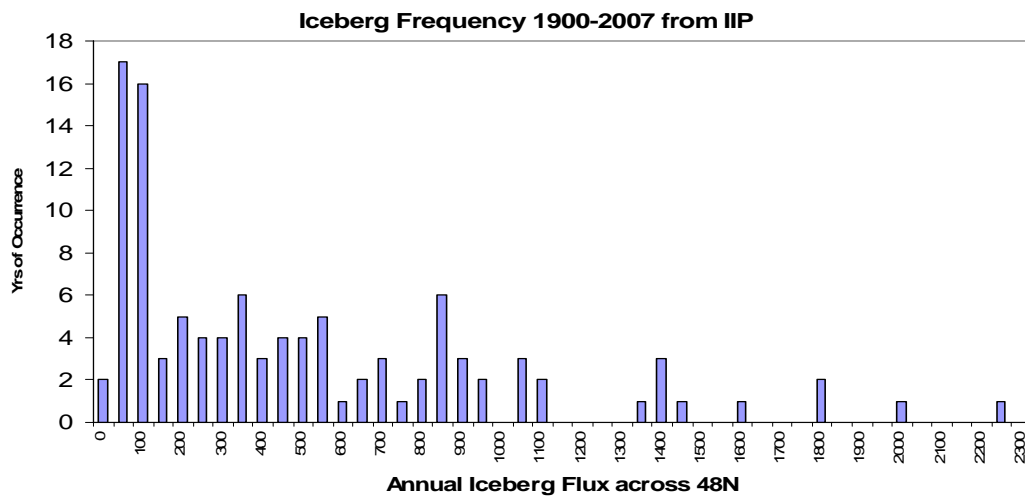
And so it appears that sea ice through its ability to prevent iceberg grounding and subsequent melting on shallow continental shelves, together with its capacity for reducing free-drifting deterioration rates by suppressing sea surface temperatures and wave heights – is the primary environmental driving force behind iceberg flux at 48N. Remarkably, the empirical formulas used by Marko et al. to model seasonal and interannual iceberg flux variations explain the phenomenon accurately without consideration for fluctuations in upstream iceberg supply/production. In this way it can be inferred that variation in glacial advance rates and iceberg calving at glacial termini in Greenland have little if any effect on flux below 48N. At least according to the statistics available to Marko prior to 1994.

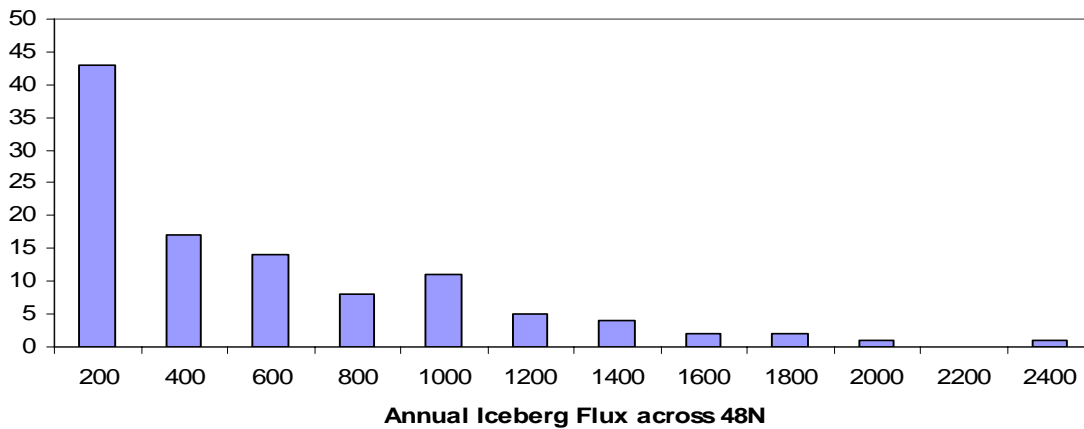
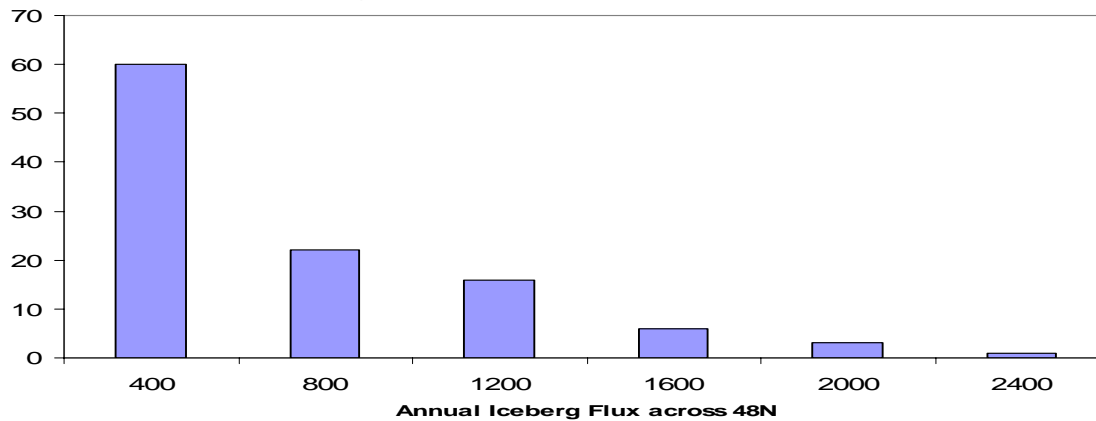
The large regional ice extents in the mid-80's through to mid-90s corresponded closely to the century high period of iceberg flux, and the period between 1941 and 1967 with

significantly lower ice extents clearly corresponded to the significantly lower numbers of icebergs in that timeframe. Sea temperatures were inversely proportional to ice extent as expected; however, the relationship of sea ice coverage represented by DSII to global mean temperatures was the opposite. Available data suggests that for the period between 1950 and 1990 the affect of Global Mean temperature changes was to have an opposing influence on Labrador Sea surface temperatures and sea ice extents. It is quite uncertain whether this coupling continues to be the case as there have been historic lows in Baffin Bay ice indices in recent times while global temperatures appear to have climbed. The time scale of these recent events (within the past decade) may be too short to determine whether solar activity is responsible, or whether an anomalous and/or anthropomorphic global greenhouse effect is at work. In any case, the conclusion is the same – ***sea ice severity is the primary control agent for iceberg flux, and the sun is implicated as the primary controlling agent of sea ice.***

Apparent Modal Behaviour

The last comment on this investigation of iceberg climate is on a curious result noticed while plotting histograms of the number of years in which certain numbers of icebergs were observed. Below, the IIP flux data has plotted four times with bin size being the only dependant variable:



Iceberg Frequency 1900-2007 from IIP**Iceberg Frequency 1900-2007 from IIP**

By plotting in this way iceberg flux rate at 48N gives the subtle impression that it occurs naturally in multiples of around 450. With the exception of the many years in which fewer than 100 bergs were sighted – the modes of the distribution show highest annual frequencies for 400, 900, 1400 and 1800 bergs respectively, with the furthest outlier at 2300. This trend is more apparent in the first two histograms and is not present in the fourth. Whether this is a real, statistically relevant result or the artifact of plotting coincidence and bin size selection is certainly debatable. It would be interesting to speculate on the cause of such a thing if it were indeed proven to be real. The author plans to do follow on work on this subject.

ICEBERG MODELING STRATEGIES FOR CLIMATE CHANGE

Previous sections of this report describe

- the installation and checking of the *localberg* model,
- an extension of sensitivity runs aimed at isolating the most important environmental driving force parameters,
- an experiment involving ranges of inputs and subsequent ANOVA work to see if parameters are processed within the code in a way that approximates the physics intended,
- and then an overview of the iceberg climate and driving forces that should be considered when investigating long term shifts in met-ocean conditions.

Reflecting on the results of this work leads one to ask the following questions:

1. Is the CIS model code preferred for advancing climate study work in light of the inter-annular characteristics identified earlier in the study?
2. What should be done here to facilitate the mandate of this project?
3. Are there improvements or changes to the physics in the model that should be made at this point if new code approaches are to be undertaken?

(1) The use of the *localberg* model for experimenting with hypothetical, representative iceberg events has been demonstrated. The tool provides deterministic results for support of hypotheses that may be conjectured and in that way is fully capable. Beyond discrete event modeling, however, lays the realm of simulation for which the *localberg* code is not preferred. It is the judgment of this Author that for advanced work on Iceberg Flux and Climate Change the preferred programming structure would have different characteristics, more in line with those in the table below:

environment	object oriented, encapsulated, methodologies with inheritance
program platform	matlab or other
data entry	deterministic or probabilistic, manual or automated, simulated or real time
data output	user defined according to input
result	text and/or plot and/or graphical
integration environment	common to international data - class and object oriented structure
simulation procedure	integrated into program environment

The outcome of using this coding approach would be to enable:

- unlimited numbers of simulated iceberg seasons with user-modified statistics of the input parameters thus enabling long term analyses
- Through a matrix based platform, the easy meshing of distributed environmental data free for users to access from archives or in real time over the internet
- The use of this data resource to mine historic states and thus calibrate model physics using hind casting techniques, and,
- the use of real time data for automated and continuous functioning with built-in feedback calibration capabilities.

An example of the type of resource available for data mining and integration is the North American Regional Reanalysis (NARR) environmental data resource. The NOMADS framework that NARR uses is, “... a distributed data system that promotes the combining of data sets between distant participants using open and common server software and methodologies. Users effectively access model and observational data and products in a flexible and efficient manner from archives or in real-time through existing Internet infrastructure.” The met-ocean data for the region of interest in this study is, apparently, updated every 3 hours, and is thus, not truly real-time.

(2) Though somewhat beyond the mandate of this work, but as a direct result of the lessons learned within it, iceberg drift and deterioration physics as used by the Canadian Ice Services have been programmed in Matlab. It is the intention of the author to use this code to pursue advanced iceberg simulations outside the scope of this project but for the benefit of the CIS over the longer term. A Matlab approach was used owing to its flexible user interface which allows the model to be manipulated easily and for graphical representation of results. A student researcher Evan Martin, provided technical support with this work and must be credited with translating many conceptual plans into functioning results.

Within the object oriented programming approach Environment and Iceberg classes have been defined so that a large number of inputs can be handled easily and the defaults can be identified for missing inputs. Both drift and deterioration models are implemented as a single Method – of the Iceberg class. The Forecast Method solves the coupled ordinary differential equations which govern the two Methods, using built-in ODE solvers. The Forecast Method has the ability to simulate quasi-dynamic environments by using multiple environmental inputs and dividing the total forecast time into sub-steps, each with a unique environment.

At this point the use of Environmental objects only allows for environments that are static in both time and location. This is fine for the bathymetry and land masking which have now been incorporated. However, other dynamic environments require attention - a method for correcting this problem is proposed in which maps of environmental properties are used as inputs instead of discrete values. Data from the NARR described above are the intended target of this exercise. This action allows for the full spatial extent of the region to be modeled, while the temporal changes between reloading of

data maps would still have to be resolved by using time-intervals. The use of real-time, or at least frequently updated, data maps would solve one of the key issues – that of interdependency or parametric correlation. Presently it is not known whether qualifiers within the *localberg* code prevent correlated parameters from diverging or varying in unrealistic and improbable ways.

(3) The following questions, being somewhat rhetorical in nature are intended to subjectively comment or raise attention to certain aspects of the model physics as requested in communication with the client, CIS. Though provocative for those on the receiving end, they are intended to lead to constructive results and dialog:

Where so few environmental driving parameters are relevant to the combined drift and deterioration model output is it not prudent to consider replacing the discretized approach with a simple consolidated empirical equation? And further, is it dangerous to separate the various categories of deterioration through a subset of formulas, and likewise do the same with drift – where in fact nature does not apply its driving forces in this way? The state of an iceberg and the state of the environment as described by wind, waves, current and temperature are intertwined in a complex correlated continuum which may best be described in a probabilistic framework – rather than a discrete theoretical one. Are statistical approaches like multivariable regression formulation or learned behavior through neural networks a more pragmatic approach to this dilemma?

Given that sea ice plays such a dominant role why is there no direct accommodation of it? And are the environmental driving parameters that are used to infer the effects of ice, sufficient or should the model view these things in reverse, with sea ice being the primary input? The low latitude mandate of the CIS does not sufficiently explain the absence of ice in the model as ice is clearly dominant when it is present, ice coverage and type are perhaps the most readily available data on hand for the CIS, and it is nowhere obvious that localberg is described as being limited in its range of applicability.

Are ‘forced’ and ‘buoyant’ convection phenomena mutually exclusive and should the formulas be linked? Are the uncertainties with these approaches so high as to render the formulations entirely empirical in nature, and thus inextricably coupled?

In the absence of any capability or accommodation of solar insolation as it relates to weather, is it reasonable to suggest that it is represented in this model? By extension, where parameters are incorporated into the model but are shown to be of negligible value to the variance of output should they remain as stated, or should they be consolidated into dimensionless empirical coefficients, constants or approaches? Is it of value to have parameters included by name, and not by real affect, or is this potentially hazardous to model evolution and improvement?

What other fields of science require this sort of programming and forecasting and how is it achieved? Are the iceberg drift models now used in the Barents Sea by Russian researchers of any value or applicability in this area?

How much field data is required to achieve desired levels of confidence in modeling and how may it best be gathered?

ICEBERG DETERIORATION FIELD WORK - JUNE 2007, ST. JOHN'S

This section of the report describes previously unreported results of fieldwork involving the monitoring of a grounded iceberg near Signal Hill in St. John's, NL in June 2007. The analysis reported here is limited to calving frequency as it relates to previous work by this author through collaboration with Ballicater (1998, 2004, and 2005)

On the morning of June 3rd 2007 an iceberg was observed in the distance from Signal Hill St. John's as it drifted a general course to the South West. There were approximately two other bergs within sight at that time. Fortuitously, the author photographed this distant iceberg and returned the next day to find that it had drifted in to shore and apparently grounded in the general vicinity referred to as Quidi Vidi. The berg was again photographed in the same area the following day and the author then contacted the CIS with a request for the expeditious return of camera equipment used in prior time-lapse field work. Continued daily trips to the lookout confirmed that the berg was indeed grounded and likely to stay as it had drifted into place as a tabular one. These, is has been observed will remain in place through a considerable period of deterioration owing to the fact that in tabular form a minimum draught is achieved and subsequent melting which may cause imbalances usually serve to increase the downward reach of one side or another of the ice mass.

On June 9th the equipment arrived from the CIS and through a prior agreement with National Parks Historic sites two independent recording stations (laptop, tripod, video camera . . .) were configured and launched from within the Marconi room in Cabot Tower. Approximately Parallel camera records for 9 complete days were managed through twice-daily visits to the Tower. As usual, fog, darkness and iceberg repositioning out sight meant that a cumulative total of only 72.25 hours of unambiguous eligible records were obtained. In all instances the better of the two views from the camera setups was selected for any particular recording interval. (The strategy with two cameras being a near field view with good resolution and high risk of iceberg departure from the viewfinder, and, a wide angle with poorer resolution but a fighting chance of keeping the berg within sight during unmanned periods.)

In a manner similar to that described in some detail in previous work (Ballicater 2004, 2005) the time lapse data were reduced and scrutinized for calving events. The observed events have been categorized as small, medium and large according to the following classification:

- | | |
|--------|---|
| Small | - Single growler, few bits of brash. |
| Medium | - A few large pieces, several smaller and a noticeable halo of brash in the surrounding water. |
| Large | - Noticeable change in berg shape and orientation, large quantities of floating ice rubble of all sizes, some sintered piles of brash noticeable. |

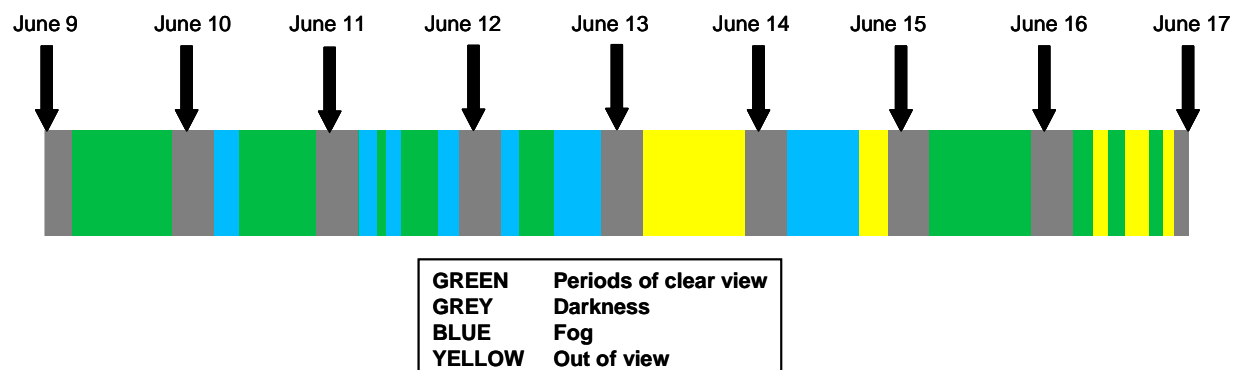
Summary of Calving Events at Signal Hill

The table below lists the events noted from the record:

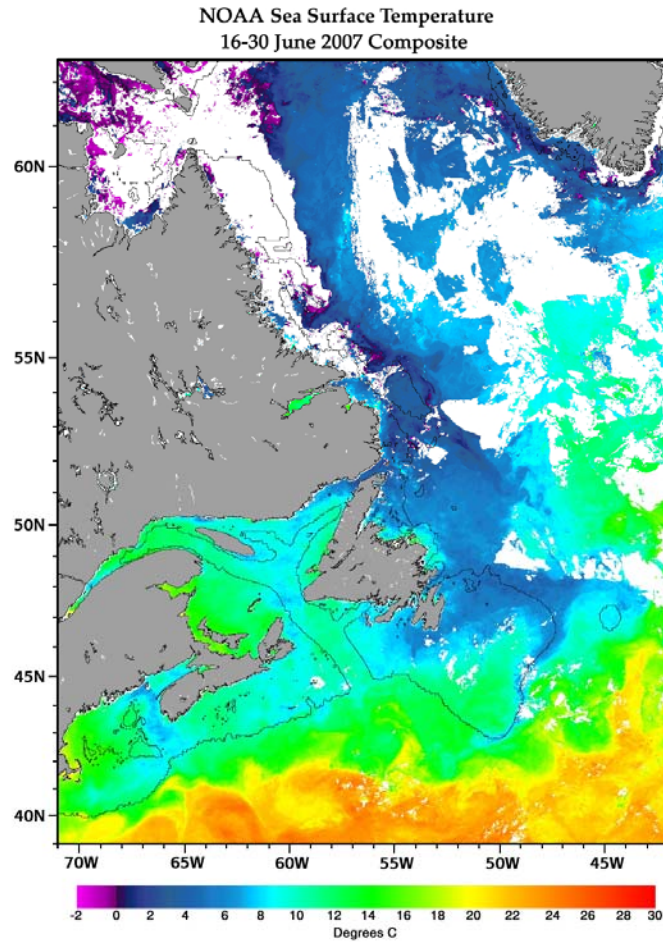
Calving Events	
Date/Time	Size
6/09/10:04	Small
6/09/13:55	Small
6/09/15:22	Small
6/09/16:23	Medium
6/09/17:01	Small
6/09/21:28	Small
6/10/10:21	Small
6/10/11:06	Medium
6/10/17:11	Large
6/10/18:13	Small
6/11/4:41	Small
6/11/7:45	Small

6/11/14:36	Small
6/11/16:31	Large
6/11/17:07	Small
6/12/9:01	Medium
6/12/10:38	Small
6/12/11:31	Medium
6/12/12:58	Small
6/15/9:34	Small
6/15/11:42	Large
6/16/8:00	Medium
6/16/11:30	Large

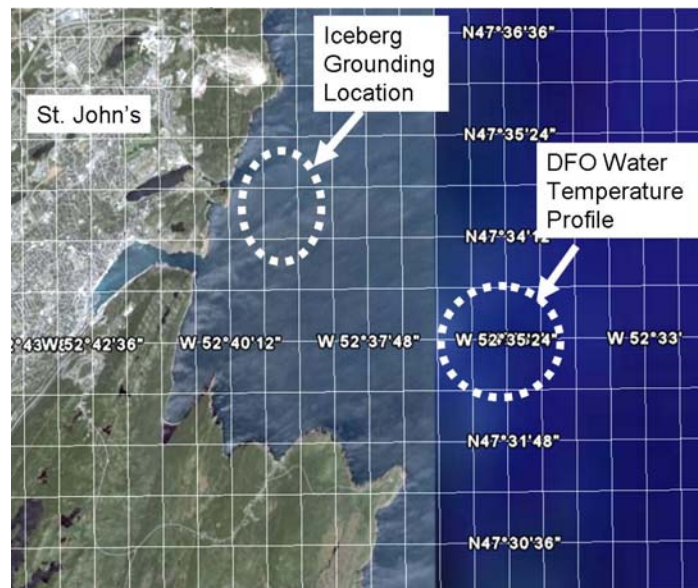
These results have been graphically represented below on a timeline whereby periods of valid data are differentiated from lost time.



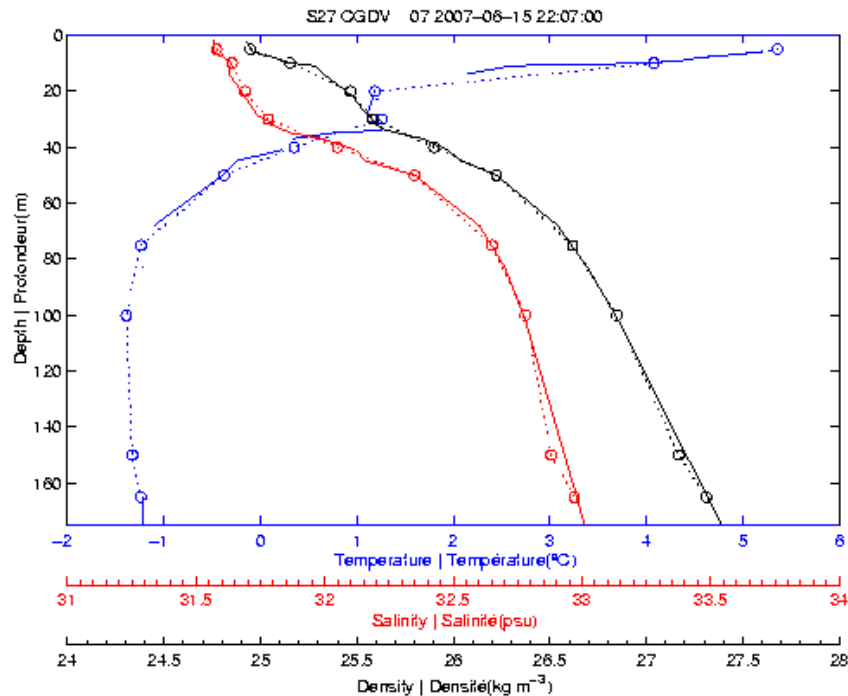
Fisheries and Oceans Canada records bi-monthly sea surface temperatures in the oceans surrounding the country. The temperatures are recorded by satellite over a period of half a month and are then averaged and placed in a composite is shown in the figure below. The composite for June 1 – 15th showed an average temperature of 7°C, and the composite for June 15 – 30th displayed an average temperature of 10°C. Given the observation period extended from June 9th to June 17th it has been assumed that an average temperature of 8°C was experienced during the observation period.



The Marine Environmental Data Service of DFO provides hydrographic information for many sites, and significantly this includes data from a station not four kilometers from the berg grounding site. On June 15th, 2007 at 47.55°N and 52.59°W a STD profile was obtained in the vicinity shown on the figure below:



The STD profile plotted below indicates a near surface temperature between 5 and 6 degrees C though the resolution at this depth is vague, and it appears readings above 5 meters are non-existent. Regardless, extrapolation suggests the NOAA data for SST is a match and for future work the STD profile over depth may be of importance for re-analyzing this deterioration event.

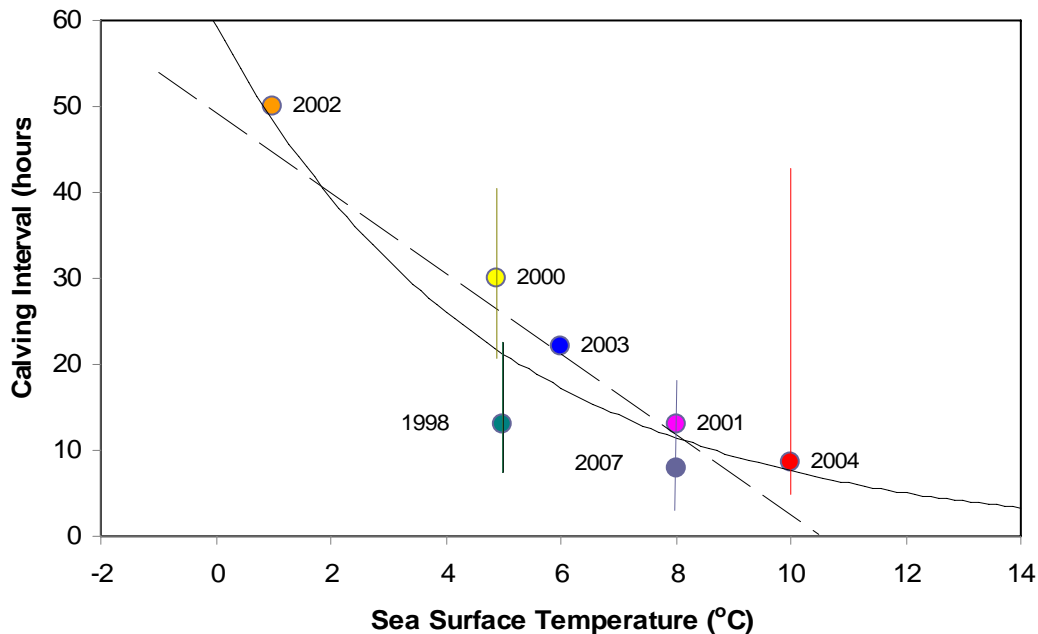


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Analysis and Discussion

During the 72.25 hours of observation time 14 small, 5 medium and 4 large events were recorded. The average calving interval during this time period for both medium and large events combined was 8.0 hours. The plot below indicates the relative goodness of fit of the present data with past work. The round markers on the graph represent the calving intervals for medium and large events. Only the medium and large events were used because it is unlikely that the smaller events were able to be seen during the observations from the air. Upper and lower limits have been added to the 2007 data to represent the range of the actual calving rate. The upper limit is developed by recording the large calving events. During the 2007 observations there were 4 large events leading to a calving interval of 18.1 hours. The lower limit is developed by recording all (small, medium and large) calving events, this leads to a calving interval of 3.1 hours. The upper and lower limits have been displayed on Figure 3 for the 1998, 2000 and 2004 data points as well. Of note: previous investigations resulting in calving interval data have been undertaken from both air and on land. The calving intervals from 2000 to 2003 were obtained from CFR flights and the data in 1998 and 2004 were obtained from video observations much like the present 2007 data.



The straight dashed line on the graph represents the best linear fit through all data points. The equation of the line is given by:

$$t_c = 49.2 - 4.66T_w$$

Where t_c is the calving interval in hours and T_w is the surface water temperature.

Reasonable agreement results from the linear model ($R^2 = 0.8084$) but it poses problems reconciling with natural tendencies towards the extremes. To avoid a calving interval tending towards zero as temperatures rise past 10°C , and, appreciable calving rates in waters well below zero, a declining exponential best fit was applied with the resulting curve formulation:

$$t_c = 59.4 * e^{(-0.205T_w)}$$

Whether this fit is better or not within the context of CIS iceberg modeling is unknown. By comparison, in Ballicater (2004) similarly derived empirical formulas from the 4 CFR data points were expressed as:

$$t_c = 55.3 - 5.3T_w \quad t_c = 62 * e^{(-0.20T_w)}$$

Note that subtle changes in coefficients and exponents have resulted from the addition of new data to the analysis.