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Observations and Modelling of Bergy Bit Drift

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ABSTRACT

The drift of icebergs has been studied extensively and drift models have been developed and tested for both scientific and engineering applications. These models have focused primarily on icebergs, and while the general principles of the models should apply to ice pieces of all sizes, comparatively little work has been done on evaluating forecast performance for small ice pieces (bergy bits and growlers). There has also been relatively little work on the fundamental nature of bergy bit drift, and little is known about drift speeds and directions, and how these relate to environmental driving forces in the open ocean. This study utilizes a data set collected using air photo surveys off the north-east coast of Newfoundland in the years 2000, 2001, 2002, and 2003. In each of the surveys all calved ice pieces with waterline lengths greater than 2.65m were mapped on 2 photo-mosaics taken 2 to 3 hours apart. In total, the positions and lengths of about 1000 ice pieces were recorded. Conditions during the measurement programs included a range of water temperatures (roughly 0°C to +8°C), and sea states (roughly 0.25m to 3m wave heights). The surveys yielded information on the production, drift, and deterioration of bergy bits and growlers calved from parent icebergs. This paper presents an analysis of the general properties of calved ice pieces, their drift characteristics, and the accuracy of a dynamic iceberg drift model in hindcasting bergy bit drift. It is shown that on average the drift model does reasonably well at hindcasting drift, but occasionally produces hindcasts that have very large directional errors. A discussion of potential causes of these large errors is presented.

KEY WORDS: Icebergs; Bergy bits; Growlers; Drift.

BACKGROUND

Bergy bits are small pieces of glacial ice the calve from glaciers or icebergs. MANICE (2005) defines a bergy bit as "*A piece of glacier ice, generally showing 1 to less than 5 m above sea-level, with a length of 5 to less than 15 m.*" In the present study we use a slightly broader definition and include ice pieces up to about 20m in length and down to lengths < 5m, which would normally be called "growlers". We also use the catch-phrase 'calved pieces' to refer to all ice calved from parent icebergs. Although they are small in comparison with their parent icebergs, they still have substantial mass and can experience large wave-induced motions and can therefore cause damage to ships and some types of offshore structures. They are also much more difficult to detect than icebergs, which can decrease the time available for ice management operations.

The drift of icebergs has been extensively studied, and drift models have been developed for several applications. These include scientific studies, such as the contribution of icebergs to freshwater input to the surface layers of the ocean, hazard avoidance, such as the International Ice Patrol which uses drift models to 'nowcast' the Limit of All Known Ice (LAKI), and in iceberg management activities where drift models assist in the decision-making process. Deterministic, physics-based models are most common, but statistical models and hybrid statistical/physics models have also been developed or proposed. Some work toward the development of ensemble iceberg forecast models has also been conducted (Allison et al., 2014). These models have focussed primarily on icebergs, and while the general principles of the models should apply to ice pieces of all sizes, comparatively little work has been done on evaluating forecast performance for small ice pieces. In addition, there has been relatively little work on the fundamental nature of bergy bit drift, and little is known about drift speeds and directions, and how these relate to environmental driving forces in the open ocean.

This study utilizes a data set collected off the north-east coast of Newfoundland in the years 2000, 2001, 2002, and 2003. In the spring (May or June) of each year air photo surveys were conducted to collect information on the production, drift, and deterioration of bergy bits and growlers calved from parent icebergs (Crocker, 2000; Crocker, 2001; Crocker, 2002a; Crocker, 2003). Data from these four measurement programs covered a range of water temperatures (roughly 0°C to +8°C), and sea states (roughly 0.25m to 3m wave heights). The primary objective of the work was to collect data for the verification of a bergy bit melt model (Crocker and English, 1997, Savage et al., 2001), but the data can also be used to investigate the general characteristics of calved pieces, their drift, and to evaluate the accuracy of drift model hindcasts. In this work the model being evaluated in the North American Ice Service (NAIS) iceberg drift model.

DATA COLLECTION AND ANALYSIS

Approach

The approach was to identify icebergs that had recently calved and then use a mapping camera to photograph the entire area of seas surface covered by the calved material. After some intervening time, typically between 2 and 3 hours, the iceberg was revisited and a second photo survey was conducted, again covering the complete area of sea surface covered by the calved ice pieces. The GPS position of the parent iceberg was recorded during both surveys and the absolute positions of each calved piece was determined from the photo-mosaics by their position relative to the parent iceberg. The drift speeds and directions were determined from the change in positions and the time interval between surveys. For the deterioration studies (Crocker and English, 1997, Savage et al., 2001) it was important to be able to identify individual pieces on both surveys and this was done by sorting the pieces by size and assuming the largest piece on survey 2 was the largest piece on survey 1 and so on down to the smallest pieces measured on the photographs. However, this was not required for the analyses of drift presented in the present study.

Aerial Photography

The platform used to acquire the photographic images was Environment Canada's dedicated ice reconnaissance aircraft (call sign 'CFR'). The aircraft was equipped with a Zeiss RMK-23 9×9 inch mapping camera. The camera's focal length was 153mm, and all photographs were taken from an altitude of 2200ft (670m) so the nominal footprint for the photos was 1 km × 1 km, and the nominal photo scale was 1:4375. To minimize the costs of the data acquisition program, the photographic surveys were coordinated as much as possible with CFR's routine iceberg reconnaissance activities. The target overlap on both the leading edge and sides of the photographs was 20%.

For efficiency, flight lines were set up along the long axis of the calved piece field. One flight line was usually sufficient for the first surveys and 2 to 4 lines were required to capture the field on the second surveys (the pieces were more widely dispersed). The number of photographs required per survey ranged between 3 (on a 1st survey) and 45 (on a 2nd survey). The locations of the surveys are shown in Figure 1.

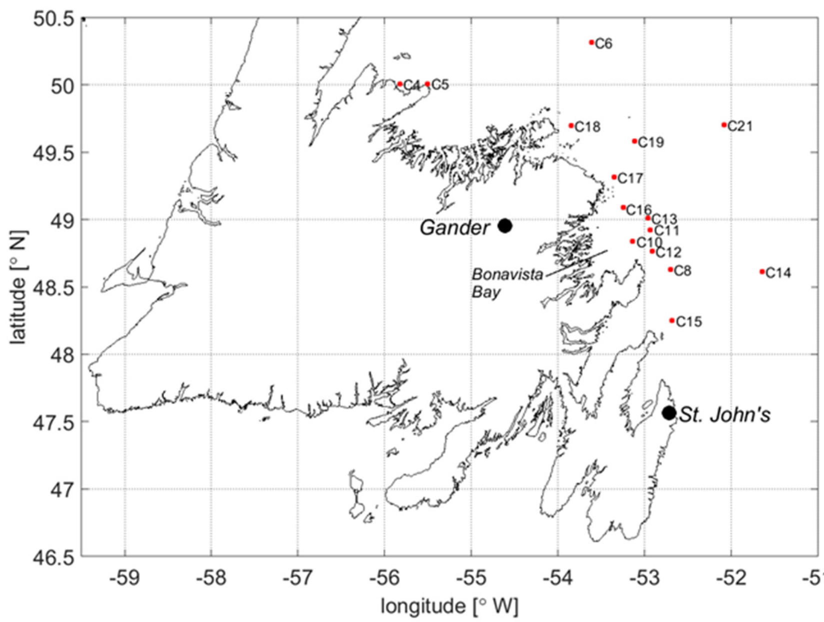


Figure 1. Map of Newfoundland showing locations of surveys used in the present study.

Measurements Methods

The large format (0.23m × 0.23m) photographs were collated to produce photo-mosaics of the complete area of sea surface covered by calved ice pieces. Size and position information was extracted from the photo-mosaics. The 2000, 2001, and 2003 data sets were analysed manually with the calved piece lengths measured with a magnifying comparator and positions measured with ruler. The large number of images collected during the 2002 field program necessitated the use of a semi-automated procedure to extract the calved piece information. For the 2002 data the photographic prints were scanned at 2400 pixels per inch using a Microtek SM 9800 XL scanner. A commercial image analysis software package called Image Tool® was used to extract position, length, width and particle orientation from electronic copies of the photographic prints. Prior to the analysis each scanned image was divided into 4 sub-images because the software would not function on files the size of a full photograph. Two different macros were used. A built-in Image Tool® function was used when the ice pieces were distinct objects and the software could distinguish between particles. This function automatically measured the desired quantities for all pieces in the selected image area. A custom macro was written to extract information when the ice pieces were close together. In these cases, individual pieces were identified by eye, and the operator used mouse clicks to mark the long and short axes of the pieces. The macro converted these to length, width, and orientation, and recorded the *x*-*y* position at the centre of the long axis. More detailed information on the data extraction process is given in Crocker (2002b).

Combined with ancillary information such as water temperature, sea state, and GPS positions, the ice piece data were used to generate information on the size distribution of the calved pieces, relative and absolute drift of the parent icebergs and the calved pieces, the mass calved per event, calving frequency, and the melt rate of the calved pieces. Table 1 shows the observation data sets along with associated sea surfaces temperatures and wave heights (combined wind waves and swell), and which data sets were used in the drift model evaluation. Other subsets of the data were used in the analyses of bergy bit parameters as indicated in the figure captions.

Table 1. Summary of calved piece surveys.

Year	ID	Date	SST_{mod} [°C]	SST_{AXBT} [°C]	H_S [m]	Use in Drift Model Evaluation
2000	C1	20/6/00	~5	4.30	1.0	Not used, parent iceberg positions not accurate
	C2	21/6/00	~5	n/a	0.5	Not used, parent iceberg positions not accurate
	C3	21/6/00	~5	n/a	0.5	Not used, parent iceberg positions not accurate
2001	C4	21/6/01	7.0	8.3	0.9	included
	C5	21/6/01	6.9	n/a	0.8	included
	C6	22/6/01	6.5	8.5	1.0	included
	C7	23/6/01	5.7	7.6	0.6	Not used, 2nd survey had incomplete coverage
2002	C8	5/5/02	-0.5	0.7	3.5	included
	C9	5/5/02	-0.5	0.5	1.8	Not used, 2nd calving event mixed with 1st
	C10	6/5/02	-1.1	n/a	2.9	included
	C11	6/5/02	-1.4	n/a	2.4	included
	C12	6/5/02	-0.9	1.0	2.4	included
	C13	7/5/02	-1.4	0.6	1.7	included
	C14	9/5/02	-0.1	-0.1	2.4	included
	C15	9/5/02	0.8	1.1	1.9	included
	C16	10/5/02	-0.5	0.5	1.6	included
	C17	10/5/02	-0.5	0.2	1.7	included
	C18	13/5/02	-0.8	1.5	1.7	included
	C19	13/5/02	-1.2	1.1	1.7	included
	C20	14/5/02	1.8	2.2	1.6	Not used, some pieces completely melted
	C21	14/5/02	1.5	2.8	1.4	included
2003	C22	23/6/03	n/a	7.1	n/a	Not used, some data incomplete or lost
	C23	27/6/03	5.5	5.6	1.5	Not used, some data incomplete or lost

Error Analysis

The main source of error in the drift speed calculations is the position of the parent iceberg, from which all distances are referenced. These positions were recorded from both a hand-held GPS and the aircraft's navigation GPS as the plane flew over the iceberg. Despite the redundancy, picking the exact time the aircraft was directly over the iceberg, at an altitude of 2200ft and speed of ~120kts was more difficult that it would seem. A rough estimate of the error in the parent iceberg positions is ±200m, which represents about ~3.3 seconds of flying time. This is likely to be a random error.

Another potential source of error arises from the fact that the surveys were not instantaneous, but typically took 10-15 minutes to complete (the maximum survey duration was 28 minutes). This error would apply primarily to the positions of individual ice pieces. Since the 1st surveys took less time than the 2nd surveys, we used the mid-point of each survey when calculating the time differences.

Including some accommodation for other error sources, such as piecing together the mosaics and making the distance measurements from the photographs, we suggest the total positional error was about ±250m. For a typical speed of 0.4m/s and time between surveys of 2.5 hours the total distance travelled would be 3600m and the estimated error would be 250/3600 = 7%. We conclude that the quoted speeds are therefore typically within ±10%.

Drift Model

The North American Ice Service (NAIS) iceberg drift model (Kubat et al., 2005) was used to perform the hindcasts. This is a full conservation-of-momentum formulation that employs an implicit Euler numerical method for solving the ordinary differential equations. The ice piece length was set 10m. One change was made to the model before the hindcasts were run. The iceberg keel cross-sectional area in the model is an empirical formulation designed to give profiles that roughly match observed keel geometries. For the lowest layer, the 10m depth layer containing the iceberg draft value, a modified equation is used to terminate the keel in a meaningful manner. However, for a 10m long ice piece that only occupies one layer the calculated value of the keel area was 26m^2, which was thought to be too small. Therefore, the keel area for bergy bits was reprogramed to be $0.5L^2$, or 50m^2 for a 10m long piece. This change did not have a large effect on the results. As a check on the sensitivity of the results to ice piece length, the model was also run with $L = 5\text{m}$. This had very little effect on the results. We also checked the use of an alternate model that predicts drift based on the surface current and 2% of the wind speed. The results of this run are discussed in the next section.

Environmental Data

Hindcasts of current speed were obtained from the Canadian East Coast Ocean Model (CECOM). This is a local version of the Princeton Ocean Model. The resolution of the model is 0.1°×0.1° on a rotated spherical coordinate system, in which the equator of the rotated earth runs through the middle of the Labrador Sea in the north-south direction (Wu et al, 2012). The vertical levels are selected according to the water depth. For water depths ≥ 640 m a fixed upper layer of 64 m with eight levels and an underlying ocean with 13 levels are specified. The levels are scaled according to the thickness of the fixed upper layer or the varying lower layer. Wave data were from the WAM wave model (WAMDI Group, 1988), and wind speed and direction hindcasts were from the Canadian Meteorological Centre (CMC). These are the same inputs used operationally at CIS for iceberg nowcasts and forecasts.

RESULTS

Bergy Bit Characteristics

A histogram of the absolute drift speeds of the calved pieces is shown on the left panel in Figure 2. The speeds range from near zero to about 0.8m/s and the distribution is tri-modal. This is because there were a few general sets of environmental conditions over the course of the surveys that tended to produce a few main groupings of drift speed. The mean absolute drift speed was 0.32m/s. The right panel in Figure 2 shows the speed at which the calved pieces drifted away from their parent icebergs. This could be of interest in knowing how far calved pieces (which can be difficult to detect) might be found from parent icebergs (which are usually easier to detect). The distribution is bi-modal. Essentially the group of very high absolute speeds has be pushed to the left because the parent icebergs tended to be drifting in the same direction under large driving forces. The mean separation speed was 0.22m/s. Some of the individual calving events showed a weak tendency for the smaller pieces to drift more quickly than the larger pieces. However, this did not hold in all cases and on average there was not a discernable relationship between speed and size.

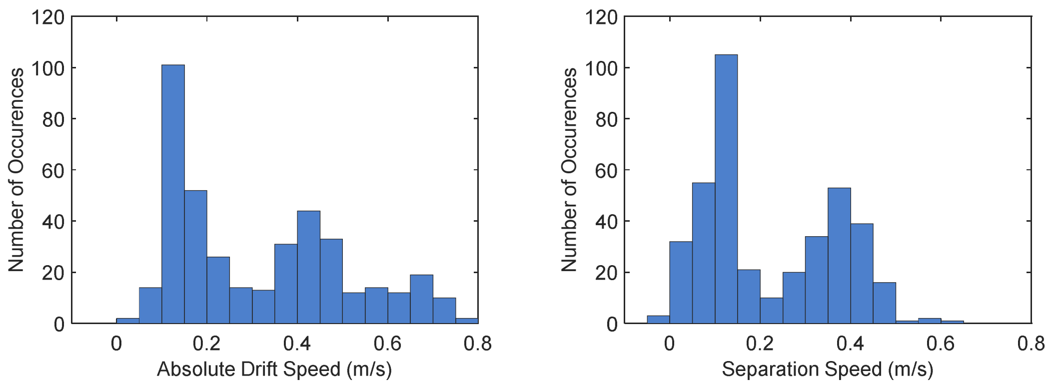


Figure 2. Histograms of the drift speed (left) and speed of separation between parent icebergs and calved pieces (right). Data from 2001, 2002, and 2003 surveys excluding C9 and C20.

Distribution fits to the length data from all surveys (both 1st and 2nd) were performed for Exponential, Weibull, Gamma, Lognormal, Power-Law and Generalized Pareto probability density functions. The length data are truncated at 2.65m and this was accounted for in the fitting procedure. It was found that the Generalized Pareto Distribution provided the best fit, as shown by the dotted line in Figure 3. The Distribution Function for the Generalized Pareto Distribution is,

$$F(x) = \begin{cases} 1 - \left(1 + k\dfrac{(x-\mu)}{\sigma}\right)^{-1/k} & k \neq 0 \\ 1 - exp\left(-\dfrac{(x-\mu)}{\sigma}\right) & k = 0 \end{cases} \tag{1}$$

The fitted distribution parameters were values $k = 0.2744$, $\sigma = 1.8577$, $\mu = 2.65$ ($n = 1028$). Also shown is the fitted exponential distribution (dashed line) which had been found to fit data from previous studies (eg. Crocker, 1993) with a lower detection threshold and that therefore included smaller ice pieces. The generalized Pareto Distribution was also found to provide a better fit to the present data than the Weibull function suggested by Savage et al. (2000). Since the measurements were taken some time after the initial calving events, the fitted distribution does not necessarily represent the distribution immediately post-calving but includes some effects of melting. Fits using only data from the first surveys also showed the Generalized Pareto distribution to be best.

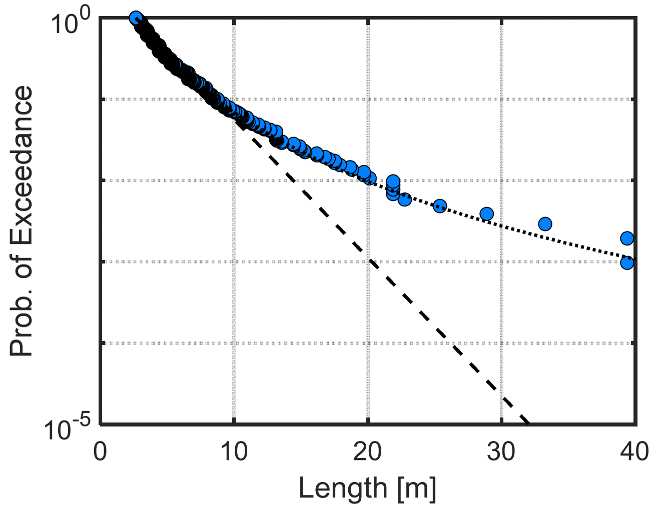


Figure 3. Length exceedance plot with fitted Generalized Pareto (dotted line) and Exponential (dashed line) distribution functions. Data from 2000, 2001, and 2002 surveys (a and b).

Figure 4 shows a histogram of the length to width ratio from the 2002 data (L ≥ 2.65m). The maximum ratio was about 6, and the mean was 1.66. The orientation of the long and short axes of the calved pieces were also recorded from the 2002 images. It was thought that there might be some tendency for the ice pieces to drift with 'beam on', with their long axis perpendicular to the drift direction. This turned out not to be the case. The orientations (not shown) were random. Investigation of the dispersion of the calved mat also failed to show any well-defined trends or relationships. In general, the area covered by calved pieces increased with time (Figure 5) but there was a wide range mat sizes and expansion rates showed no clear relationships with drift speed, or initial size.

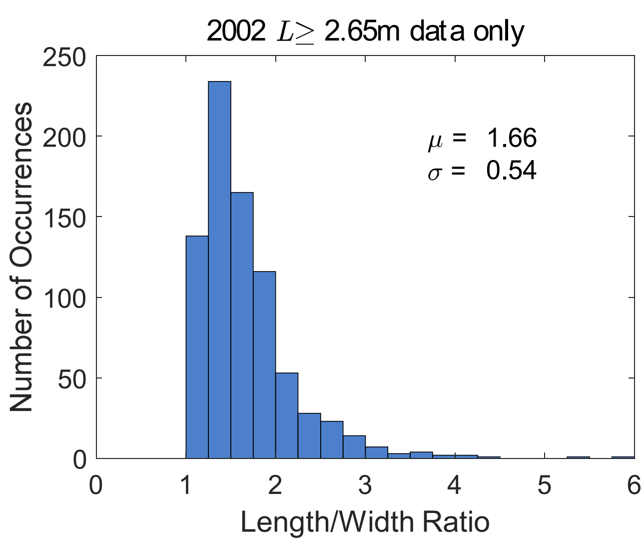


Figure 4. Histogram of length to width ratios, 2002 data only.
Data from 2002 surveys (a and b), except C9 and C20.

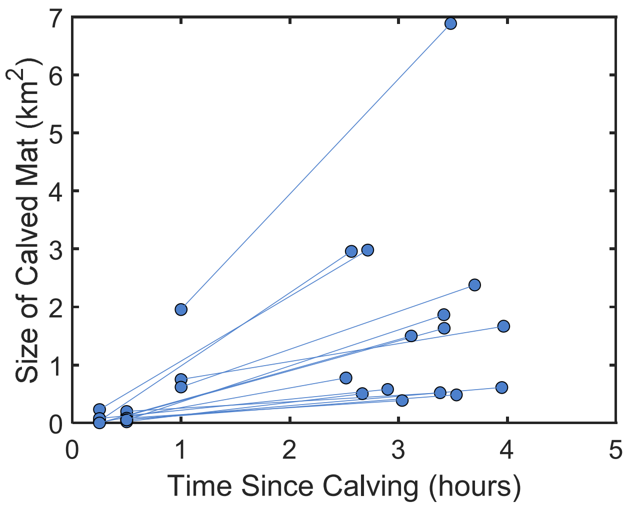


Figure 5. Calved mat size as a function of time. The initial time since calving (when the first surveys were conducted) was estimated from the spread, proportion of small brash ice particles and distance from the parent iceberg. Data from the same 15 surveys used in the drift model comparison.

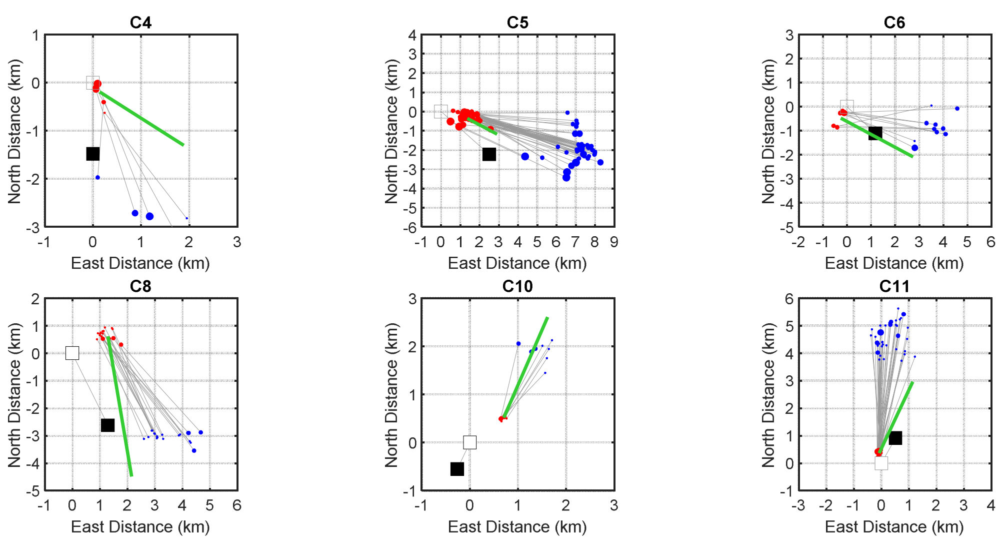
Model Hindcasts

Hindcasts were made using the NAIS iceberg model and input from CECOM, WAM, and CMC as described above. The results are shown in Figure 6 where all positions are plotted relative to the parent iceberg at the time of the first survey. The hindcasts are shown by the green lines. Hindcast positions between the start time and the time of the second survey are not shown to reduce clutter, so the lines connect the initial positions to the predicted position at the start time of the second survey. All the results shown were derived using the full iceberg model with a fixed waterline length of 10m. The size of the dots representing the calved pieces are roughly scaled by size with larger dots representing larger ice pieces. The grey lines connect ice pieces of the same rank from largest to smallest on the 2 surveys. This information was used in the studies of bergy bit melt (Crocker, 2003) but is not required for the drift analyses described in the present paper.

The plots give a general impression that with a few exceptions, the hindcast drift directions are reasonable. This is supported by Figure 7 (left panel) which shows the direction differences (observed - modelled) as a function of observed direction. *Positive* differences indicate the modelled direction was to the *right* of the observed direction. The grey colour covers the area in which the direction differences were ±22.5° or less. Forecasts in this range are generally classified by offshore operators as being 'very good' (Provincial Aerospace Ltd, 2010, personal communication). About half of the hindcasts fall in this region, and 11 of the 15 (73%) were within ±45°, which industry would consider 'useful'. The average direction difference was 0°, indicating that on average the model does quite well. But the very large standard deviation (56°) indicates there are large direction errors for individual hindcasts. Two hindcasts in particular were very poor. The C13 and C15 were +140° (to the right) and -115° (to the left) of the observed drift respectively and it is interesting to look at these 2 cases in more detail. C13 was near the mouth of Bonavista Bay and was the only survey conducted that day. The observed drift speed was relatively low (0.12m/s). The hindcast drift direction was not only very poor for the calved pieces, it was almost the opposite direction of the parent iceberg drift. With no coastal features nearby, it seems likely the errors are strictly due to a poor hindcast in either the currents or winds, or both. C15 was about 18km north east of Baccalieu Island. It is possible that this close to land the ocean model does not generate accurate hindcasts. In particular, tidal currents may be strong close to land and CECOM does not include a tidal model. Photographs of C15 taken at the time show the sea state to be quite benign, suggesting the drift was dominated by the surface current. The calved pieces drifted generally south-west while the parent iceberg, which would be more influenced by currents at depth, drifted due west. Survey C14 was conducted on the same day but farther from shore and the hindcast direction was fairly good.

The right panel in Figure 7 shows the speed differences between the observations (based on the centroid of the cluster) and the model. The mean difference is again quite small (0.02m/s), but there are significant errors with individual hindcasts as indicated by the large standard deviation (0.18m/s). There is some tendency for the speed errors to be larger when the observed speed was large. Despite a moderate absolute error, C19 is a bit of an outlier because the hindcast speed (0.26m/s) was more than double the observed speed (0.12m/s) so the error (0.14m/s) was larger than the observed speed. Another large outlier is C5 which had the largest absolute speed error. This was another case of an iceberg close to shore. At the time of the survey C5 was only 600m from shore and it is likely that tidal currents and the channeling of wind near the coastal cliffs were not accurately reproduced by the current and wind models. C19 on the other hand was relatively far from shore. Two surveys (C18 and C19) were conducted on this date (13/5/02) and in both cases the hindcasts produced drift speeds far in excess if the observed drift of most of the calved particles. The speed error for C18 appears less because one particle drifted much faster than the main group thereby extending the approximate centroid position and lessening the apparent error. Therefore, it seems likely that the wind hindcast on this date over-estimated wind speed.

As an alternative to the full iceberg drift model, hindcasts were generated with drift calculated simply as being the vector sum of the surface current and 2% of the wind velocity. The mean direction difference increased to 13°, while the standard deviation remained about the same at 56°. The increase in the mean error is somewhat misleading because the direction of one of the large outliers (C15) is greatly improved, while another (C13) is not. With one outlier on each side of zero the average error somewhat offset. The fact that the error standard deviation is about the same as that produced by the full model, even though one of the main outliers is eliminated indicates a slight increase in variability for the suite of hindcasts excluding C15 and C13.



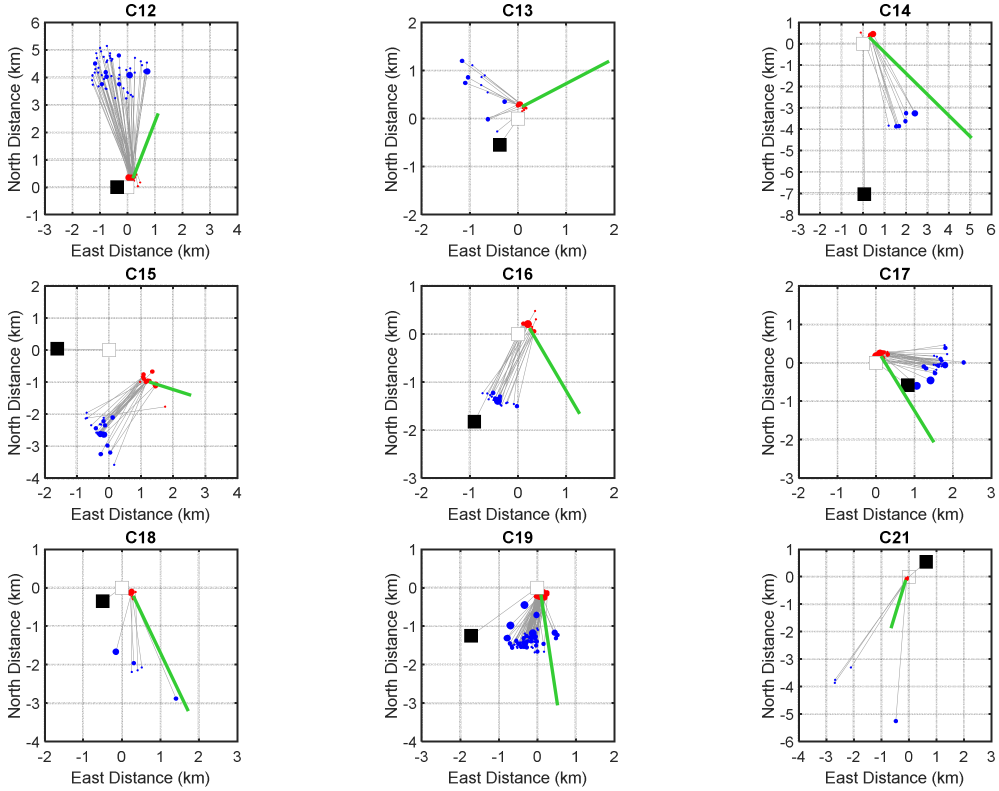


Figure 6. Plots of all observed and modelled drift tracks. □ = iceberg position at 1st survey (reference location), ■ = iceberg position at 2nd survey, ● = bergy bit positions at 1st survey, ● = bergy bit positions at 2nd survey, | = hindcast track.

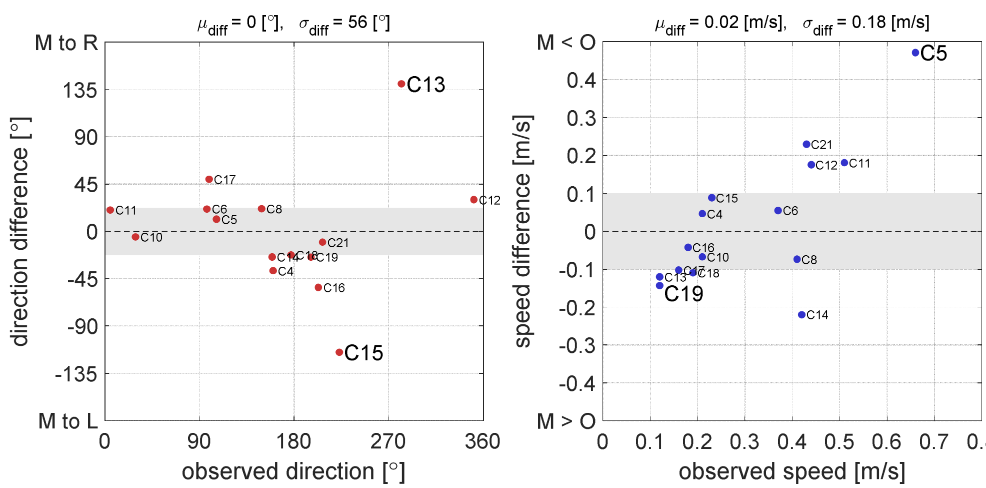


Figure 7. Speed and direction comparison: full model.

CONCLUSIONS

Repeat aerial surveys were shown to be an effective approach for determining the average drift properties of bergy bits calved from icebergs. From 15 repeat surveys conducted off the north coast of Newfoundland in 2001 and 2002 it was found the mean drift speed of calved pieces was 0.32m/s. The length distribution of calved pieces was found to be reasonably well represented by the Generalized Pareto Distribution. The mean length/width ratio was 1.66m.

The calved mats ranged in size from 0.002km^2 to about 7km^2 and showed no clear trend with environmental parameters such as wind speed, or other calved piece properties such as initial size or drift speed.

The average error in the drift direction and speed were 0° and 0.02m/s respectively. However, the large standard deviations of the errors (56° and 0.18m/s), and close examination of the errors show that individual hindcasts were quite poor. These high standard deviations are inflated by a small number of especially poor hindcasts that appear to be the result of poor wind and/or current predictions. In some cases, the large errors occurred with icebergs that were close to shore and it is reasonable to expect the regional wind and current models do not perform well in geographic proximity to land. 11 of the 15 hindcasts (73%) were within ±45° of the observed direction. Examination of Figure 7 suggests, at least qualitatively, that there was some tendency for the model to overpredict speed when speeds were low and under-predict when speeds were high.

The model performed reasonably well 'on average', indicating it would be very useful for climatological or statistical analyses, as well as the fundamental purpose of the NAIS model which is to nowcast the approximate locations of all known ice. However, the presence of outliers is problematic in some applications. For operators who wish to have accurate drift forecasts of specific, individual ice pieces it cannot be determined ahead of time if the forecast is one of the many good predictions or one of the few poor predictions. This reduces confidence in the model. For this application efforts focused on reducing the occurrence of outliers would be particularly valuable.

ACKNOWLEDGEMENTS

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