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EXTREME ICE FEATURES DISTRIBUTION IN THE CANADIAN ARCTIC

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ABSTRACT

Extreme ice features (EIFs) present one of the key ice hazards affecting the design of structures in the Canadian and Alaskan Beaufort Seas. These features include ice islands that have calved from the ice shelves of Ellesmere Island and multi-year hummock fields (MYHFs), very large and thick features formed from multiple ridging events at the outer edge of the landfast ice and solidified over years. EIFs sometimes drift into offshore lease areas of the Southern Beaufort Sea.

In 2008, a joint industry-government project was initiated to acquire extensive satellite imagery in a 100 km wide swath of the coastal corridor from the ice shelves of Ellesmere Island to Prince Patrick Island, in order to count and measure EIFs. In August 2008 there were major calvings from several ice shelves. The program captured a significant portion of the newly calved ice islands next to their parent ice shelves as well as older ice islands farther south. The imagery also captured the break-up of landfast ice and new MYHFs that resulted, as well as older drifting features.

The paper describes the satellite imagery types and coverage. Most of the EIFs were detected from Envisat images of 30m resolution. The dimensions were measured and stored in a data base. A total of 200 EIFs were identified including 40 ice islands, 93 ice island fragments and 67 multi-year hummock fields. (An ice island fragment is less than 1 km in the longest dimension). The paper describes the data base and summarizes the statistics of equivalent diameter of EIFs. For ice islands the mean and maximum equivalent diameters were 1.6 and 5.2 km. For MYHFs the corresponding sizes were 1.7 km and 13.8 km. Comparisons are made with similar data bases from the 1990s and 1980s.

INTRODUCTION

The design of offshore structures for the western Arctic of North America is likely to be governed by their interactions with very large and thick ice features referred to as Extreme Ice Features, or EIFs. An EIF is defined as an ice feature that would cause an extreme design load on an offshore production platform. It is at least 20 m thick, on average, at least 500 m in diameter and is often frozen into a large multi-year floe. EIFs include ice islands, ice island fragments, multi-year hummock fields and areas of multi-year land fast sea ice (MLSI). Ice islands originate from the ice shelves of northern Ellesmere Island. Multi-year hummock fields, or MYHF, originate at the outer edges of the landfast ice zone at the Arctic Ocean shores of the Arctic

Islands. They take the form of very rough multi-year floes containing a series of densely packed parallel ridges. Multi-year land fast sea ice, while not 20 m in thickness can contain other EIFs embedded within. All these features are known to form along the western shores of the Arctic Islands and to occasionally break free and enter the Beaufort Gyre, which in turn drifts south and west into proximity with the lease areas for offshore drilling in the Beaufort and Chukchi Seas. Figure 1 shows a regional map with key landmarks including the Arctic Islands of Canada – the main source of EIFs.

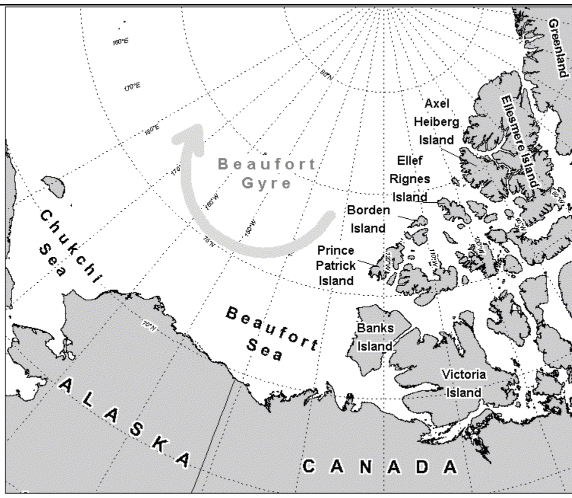

Figure 1. Western Arctic and Areas of Interest

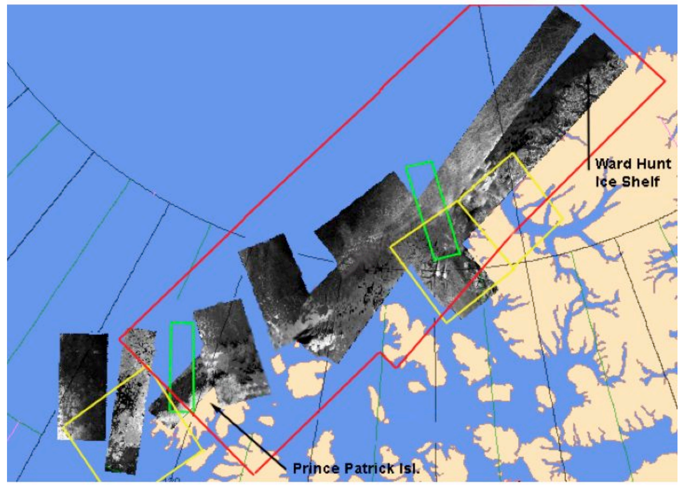

Figure 2. Satellite Data Coverage 2008, Arctic Islands

To evaluate ice loading at a structure, the statistical distributions of ice parameters are required as inputs to a probabilistic model. The key parameters are ice strength, thickness, interaction geometry, speed and feature size. Limit driving forces in the pack ice surrounding an EIF also play an important role. Thickness includes both average and local thickness (of a ridge or embedded hummock field). The type and size of features were obtained from new satellite imagery obtained in a 2008 Joint Industry Project and statistics were calculated. Figure 2 shows the location of satellite imagery purchased for this project. The objectives of this paper are to describe the 2008 program of satellite data acquisition and statistical analysis of extreme ice features, and to compare results with previous ice design statistics.

SATELLITE DATA SAMPLING AREA

The area of coverage was established with three principle objectives:

- Repeat coverage of the area covered in the previous study (Pilkington et.al. 1992)
- Complete coverage of all Ice Shelves on Ellesmere Island,
- Coverage of the off-shore/near-shore area from Prince Patrick Island to just east of the Ward Hunt Ice Shelf

Satellite data were collected using four different platforms.

- Envisat, (100 km swath, HH polarization, 30m resolution) was the main platform. Most of the area of interest was imaged using its on-board synthetic aperture radar, ASAR.
- Radarsat 2, (50 km swath, HH polarization, 8m resolution) was collected in two small areas, primarily for verification and calibration of the lower resolution Envisat imagery.

- Landsat, (100 km swath, 15m resolution) was collected due to its low cost, its ability to provide a visible-light presentation of the ice scenes, and to validate the Envisat.
- MODIS, (2300 km swath, 240m resolution) provided a broad scale snapshot of the entire area of interest, at minimal cost

Figure 2 shows a map of the area covered by Envisat (as imagery), Radarsat 2 (in green), Landsat (in yellow) and MODIS (in red).

ICE EVENTS IN THE HIGH ARCTIC SUMMER 2008

Ice Shelves of Ellesmere Island

Normally the arctic pack ice is up against the shoreline both in winter and summer, preventing the ice shelves from fracturing. Ice conditions in the summer of 2008 were unusual. A slightly offshore ice drift had created low ice concentrations or open water adjacent to the coast, and fracturing on the seaward side of the ice shelf was apparent in several areas. Figure 3 shows a sample image of the Ward Hunt ice shelf on August 1st with low ice concentration to seaward and recently calved ice islands. Figure 4 illustrates the extent of remaining ice shelves after August 1st, as well as EIFs detected adjacent to north Ellesmere Island. Note that not all the EIFs shown are ice islands or ice island fragments. The largest feature was a MYHF.

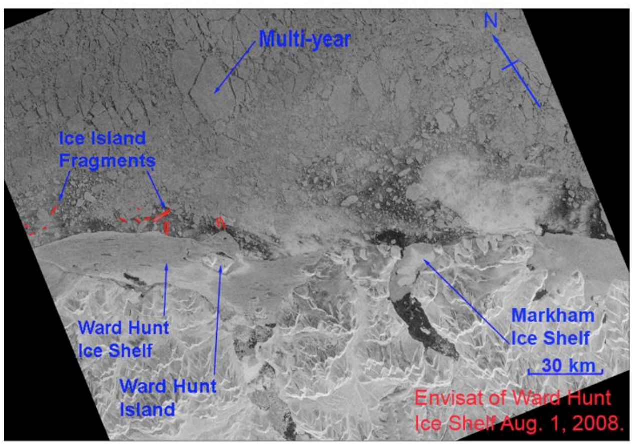

Figure 3. Ice Islands Calved - Ward Hunt Shelf

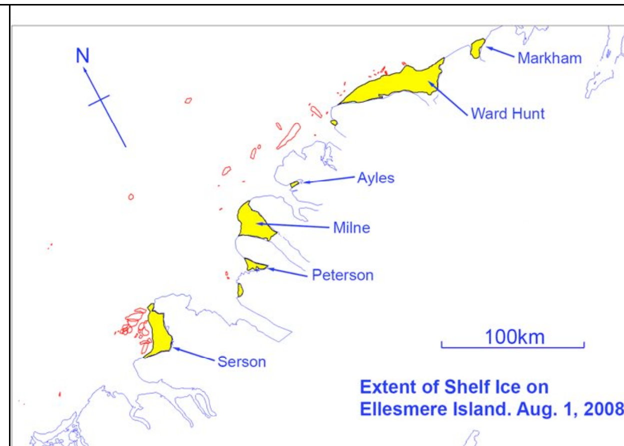

Figure 4. Ice shelf extent after Aug. 1, 2008

The August 1st Envisat survey captured major calving events at the Ward Hunt and Serson ice shelves soon after the events. A total of 130 km^2 of ice islands (>1km long) and ice island fragments (<1km long) were detected in the coastal waters and pack ice near Ellesmere and Axel Heiberg Islands on this day. However, by August 31st a total of 227 km^2 were calved from the ice shelves, including the entire Markham ice shelf, shown at the lower right of Figure 3.

Multi-year Landfast Sea Ice off Prince Patrick Island

As noted in the Introduction multi-year hummock fields, MYHFs, form at the outer edges on multi-year landfast sea ice, MLSI, which forms and normally persists for years along the western shores of the Arctic Islands. From time to time the pack ice retreats, the MLSI breaks up and the MYHFs are free to drift with the Beaufort Gyre. While MLSI exists adjacent to most of the Islands, the conditions of ice pressure are often extremely high at Prince Patrick and Borden Islands and favourable to the fomation of hummock fields. Sequential imagery obtained for the project showed that an area of MLSI adjacent to Prince Patrick Island broke up between 27 and 31 July 2008. A number of MYHFs were embedded in this ice. Thus these features were released into the pack ice. These features may also form within the polar pack ice under conditions of high pressure. MYHFs were identified as far north as Ellesmere Island in the 2008 survey, and some of these were the result of break-up of MLSI at other localities.

EIF IDENTIFICATION AND COUNT METHODOLOGY

EIFs were located, outlined and measured using a GIS program. A graphics editing program was also used to enhance or manipulate the full resolution 16 bit data so that very subtle signatures could be investigated.

Identification of ice islands and ice island fragments on radar imagery was accomplished by locating targets with some or all of the following characteristics: 1. angular shape, 2. elongated form, 3. linear fractures (resulting long, straight edges indicate a thick ice type), 4. a very strong perimeter radar return from the high freeboard, 5. complete lack of pressure ridging in the interior, 6. ribbed texture (pattern of smooth undulating ridges and troughs running parallel to the long edge).

Ice islands (>1km. in longest dimension) were relatively easy to identify versus ice island fragments (<1km). An ice island fragment can, naturally, occur in any size down to its final extinction. Through the use of the Radarsat2 data (8m resolution) verified by the 15m resolution Landsat data, ice island fragments as small as 70m x 35m were identified. Although EIFs of this size are far below what is considered a hazard, particularly when located in high northern latitudes, the "signature" of these targets provided valuable information to the interpreter regarding the sensor's response to wet shelf ice at a given radar incidence angle. Confident identification of larger more significant EIFs was consequently simplified.

A MYHF is an EIF that is principally associated with extreme on-shore pressure in a multi-year ice environment. This typically causes extreme ridging and total deformation of the ice cover; 10m freeboards in this rubble are not uncommon. The deformation occurs as multiple ridges or hummocks very close together. The features become incorporated into the land fast ice and normally consolidate over a number of years.

Subsequently these floes/areas drift free (typically in summer) when offshore winds carry them off. These features often freeze into larger multi-year floes in the fall, and are then found as separate high-return targets within floes the following year. MYHFs are distinguished from ridging by their greater degree of consolidation, by their existence as a separate target and by the occurrence of multiple hummocks/ridges rather than a single ridge line

Identification of MYHFs on radar imagery is accomplished by locating targets that have some or all of the following characteristics: 1. high radar return throughout the feature (no level areas), 2. rounded or jagged shape, parallel ridging, 4. existing as a separate target (not a ridge), 5. no evidence of a drainage pattern, 6. saturated signals in the floe (corner reflectors – standing floes, hummocks).

EIF DATABASE

During the interpretation phase of image analysis, individual EIFs were identified and outlined as polygons whose attributes were stored in different layers in the GIS program. The following set of parameters was recorded in a spreadsheet.

1. Feature ID No. 2. General area, 3. Feature type (ice island, ice island fragment, MYHF, re-entrant *, 4. Was it contained in a larger floe, 5. satellite image ID (date and time), 6. originating ice shelf if known, 7. Date, 8. Latitude, 9. Longitude, 10. Perimeter length (output from the program), 11. area, A, (output from the program), 12. roughness indication (low, medium or high).

(N.B. Re-entrant ice, marked with * above, is defined as ice shelf ice formed from multi-year sea ice that attaches to the main ice shelf due to onshore pressure and freezing. Over tens of years it attains surface undulations and thickness increases from snow accumulation and bottom accretion, and is said to have "re-entered" the shelf environment).

In a post-interpretation phase, these dimensions were measured: major axis, minor axis and length, L, the maximum linear dimension.

Definitions of these 3 terms are illustrated in Figure 5. The centroid of each floe outline is found from an algorithm within the GIS program. The moment of inertia (or second moment of area) is calculated. The major and minor axes pass through the centroid and are the principal axes of inertia. These are also called the axes of symmetry and each axis divides the plane area of the floe into two equal parts. The length, L, is a straight line connecting the two farthest-apart points in a feature. The length may or may not pass through the geometric centre and will always be equal to or greater than the major axis.

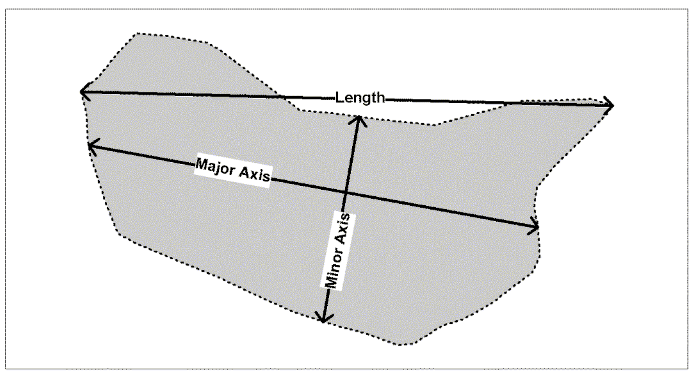

Figure 5. Definition Sketch: major axis, minor axis, length

Other geometrical parameters were calculated but for the purposes of this paper, and in order to compare with previous studies, the most important is equivalent diameter.

Equivalent diameter, $\mathbf{D_{EQUIV}}$, (in km) is defined as the diameter of a circle of the same area as the EIF, and is equal to:

$$\mathbf{D_{EQUIV}} = 2 * (\mathbf{A} / \pi)^{0.5} \qquad (1)$$

Where **A** = area of EIF in km^2

EIF POPULATION AND SPATIAL DISTRIBUTION 2008

Data from the radar imagery was logged in an Excel database. A total of 200 EIFs were detected in an area of 183,980 km^2. The resulting breakdown by EIF type is.

- 40 Ice Islands (L > 1km)
- 93 Ice Island fragments (L < 1km)
- 67 MYHFs (L > 500m)

The offshore area adjacent to the Arctic Islands was divided into 3 Zones. Zone 1 covers the coastal area from Prince Patrick to Borden Island. Zone 2 is from Ellef Ringnes to Axel Heiberg Island. Zone 3 is offshore Ellesmere Island.

Table 1 lists the numbers of EIFs found in each zone and the numbers greater than 500m in length. Note that though Zone 2 had the largest number of EIFs, it had the smallest number with a diameter larger than 500m and by far the smallest total area of EIFs.

Table 1 EIFs 2008 Divided by Zone

Zone	# of EIFs	# of EIFs of L>500m	Total Area EIFs (km^2)
1. Prince Patrick I to Borden I	57	46	143.57
2. Ellef Ringnes to Axel Heiberg	73	30	12.86
3. Ellesmere I	70	61	360.66
All	200	137	517.09

As might be expected so soon after the calving events, most of the large EIFs were detected close to their source. Most of the ice islands and ice island fragments were adjacent to Ellesmere Island and close to their parent ice shelf. The highest population of MYHFs were located offshore Prince Patrick Island (though the two largest MYHFs were found offshore Ellesmere Island). Though the highest number of EIFs was found in the middle zone, these EIFs were much smaller on average. It is likely that these were remnants from older calving events.

EIF SIZE DISTRIBUTION 2008

The statistics of length and equivalent diameter are described for all EIFs and for individual EIF types in the plots and tables, below. Median, mean and maximum values are given in Table 2 for maximum length, L, and in Table 3 for equivalent diameter, D_{EQUIV}.

Table 2 Key Values for EIF Maximum Length, L – All data 2008

EIF Type	# of EIFs	L median (km)	L mean (km)	L max (km)
Ice Islands	40	2.1	2.8	9.8
I.I. Fragments	93	0.4	0.4	1.0
MYHFs	67	1.4	2.5	17.4
All	200	0.8	1.6	17.4

Table 3 Key Values for EIF Equivalent Diameter, $\mathbf{D_{EQUIV}}$>500m – All data 2008

EIF Type	# of EIFs	D_{EQUIV} median (km)	D_{EQUIV} mean (km)	D_{EQUIV} max (km)
Ice Islands	37	1.3	1.7	5.2
I.I. Fragments	7	0.6	0.6	0.7
MYHFs	55	1.1	2	13.8
All	99	1.2	1.8	13.8

Tables 2 and 3 show the effect of calculating the equivalent diameter and then considering only those EIFs with $\mathbf{D_{EQUIV}}$ greater than 500m. The mean, median and maximum values of D_{EQUIV}

are less than those for L for ice islands and MYHFs. Since ice islands are generally quite elongated the $\mathbf{D_{EQUIV}}$ is substantially less than L in each case. The mean length, L, was 2.8 km while mean $\mathbf{D_{EQUIV}}$>500m was 1.7 km. For MYHFs the mean $\mathbf{D_{EQUIV}}$ (>500m) was 1.8 km versus 2.5 km for **L**. The MYHFs are more elliptical and less elongated than ice islands.

By definition, an ice island fragment is less than 1 km in length. In converting to $\mathbf{D_{EQUIV}}$ the population was reduced from 93 to 7. Only the wider fragments with L close to 1 km were retained. Mean $\mathbf{D_{EQUIV}}$ was 0.6 km versus mean L of 0.4 km.

Figure 6 compares the exceedence probabilities of features of equivalent diameter, $\mathbf{D_{EQUIV}}$, greater than 500m by EIF type.

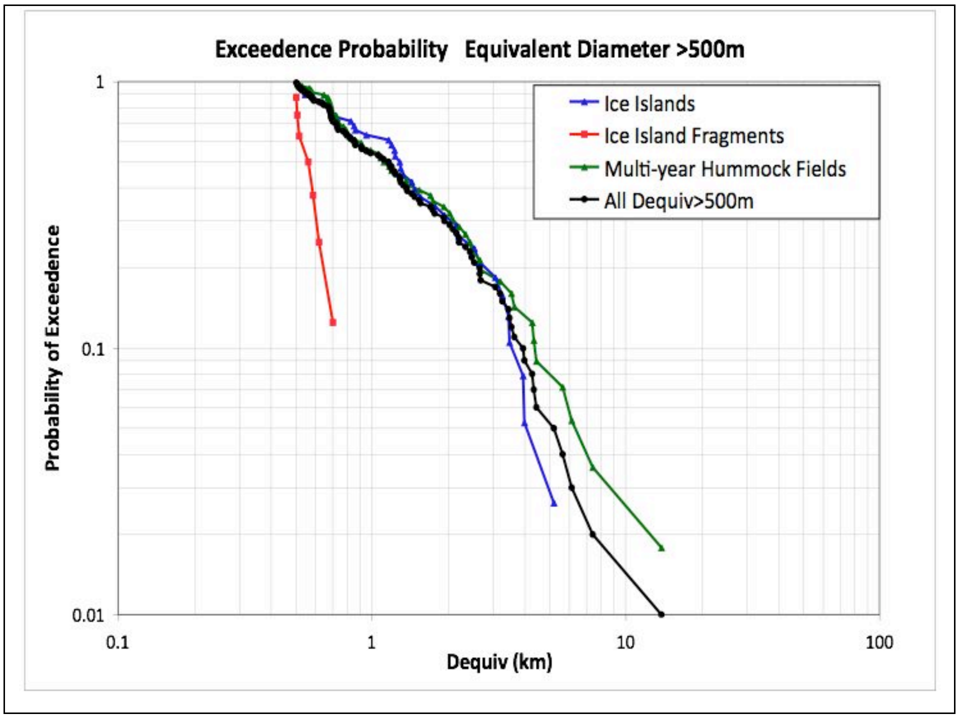

Figure 6. Exceedence Probability of $\mathbf{D_{EQUIV}}$ – all EIFs

COMPARISON WITH PREVIOUS SURVEYS

Databases from previous survey periods are included in an Appendix of Pilkington et.al. 1992. The first database covers the years 1946 to1988 and consists primarily of large ice islands. Many of these data were used to develop ice island statistics for the 1982 Beaufort Sea Environmental Impact Statement for the Canadian Beaufort Sea, in Marcellus et.al. 1982. The second database resulted from analysis of SAR imagery from 1988-1991 undertaken by Pilkington et.al. 1992. The current database for 2008 is compared with the previous surveys in terms of populations, statistics of feature size $\mathbf{D_{EQUIV}}$, and areal density.

Table 4 compares EIF populations for the 3 time periods in question. For the period 1946-1988 the focus was on large ice islands, in part due to the military and scientific applications in the early part of that era, and in part due to limitations of sensing technology. For the latter two survey periods many more EIFs were detected due to better sensor resolution: i.e. airborne SAR with resolution 12m to 25m in 1988-1991, and satellite-based SAR with 30m resolution in 2008.

Table 4   Comparison of EIF Populations for 3 Periods 1946-2008

Population Category	1946-1988	1988-1991	2008
EIFs - All All EIFs D_{EQUIV} >500m	42 38	162 149	200 99
Ice Islands & Fragments - All II & IIFs D_{EQUIV} >500m	34 30	41 28	133 44
MYHFs - All MYHFs Equiv Diam >500m	7 7	86 86	67 55
Re-Entrant Ice - All REI D_{EQUIV} >500m	1 1	35 35	0 0

Figure 7, 8 and 9 compare the exceedence distributions of equivalent diameter for the 3 time periods for ice islands, MYHFs and for all EIFs, respectively. Note that the 7 ice island fragments with $\mathbf{D_{EQUIV}}$ >500m in the 2008 survey were added to the ice island data set since these 7 would constitute a hazard to an offshore platform.

Figure 7 suggests that ice islands have been getting progressively smaller. This may have occurred for two reasons: firstly, the very large ice islands such as T3 that drifted for decades in the Beaufort Gyre, are known to have drifted out of the Arctic Ocean via the Fram Strait. Secondly, the area of ice shelf available for calving is getting smaller, and that which is available is more protected by headlands. The maximum possible size of an ice island now is probably much smaller than in previous decades. Figure 8 suggests that the size distribution of MYHFs in terms of $\mathbf{D_{EQUIV}}$ has not changed much since 1991, though the extreme MYHFs detected were larger in 2008.

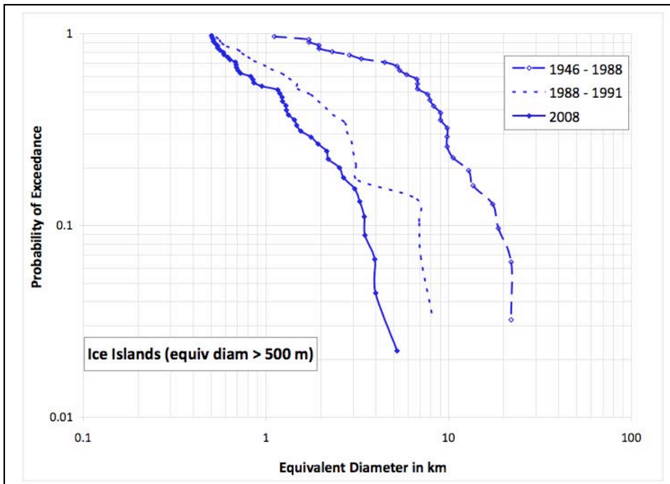

Figure 7 Ice Island Size Distribution 1946-2008

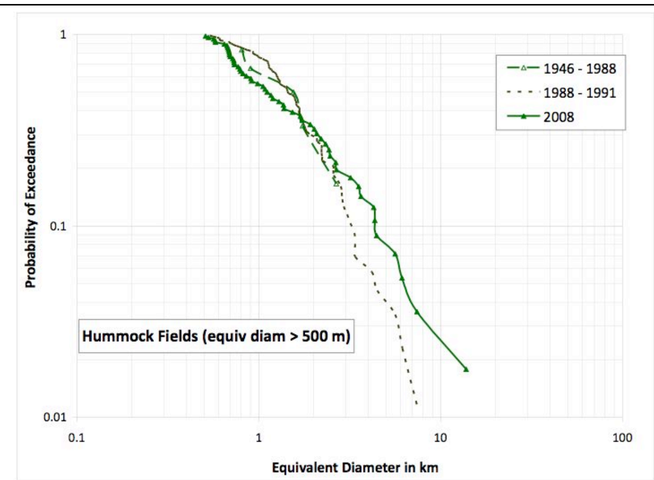

Figure 8 MYHF Size Distribution 1946-2008

Figure 9 combines the data for ice islands and MYHFs for the three time periods. The 1946-1988 data set was mainly based on large ice islands and resulted in conservative statistics for EIF size. The large ice islands have since disappeared and the size distribution curves for 1988-1991 and for 2008 are smaller, with a 1% exceedence $\mathbf{D_{EQUIV}}$ on the order of 10 km compared with 22 km.

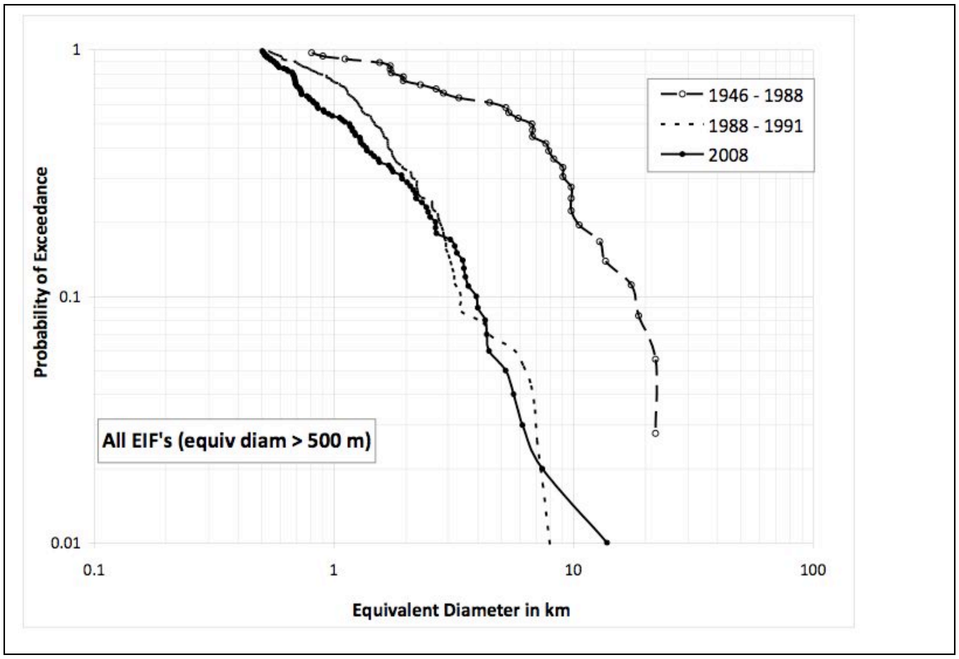

Figure 9. All EIFs Size Distribution 3 Periods 1946-2008

Finally the areal density is compared in Table 5. The areal density, expressed as the average number of EIFs per square kilometre, is a parameter that enters into the calculation of impact probability. The 1988-1991 data set combined EIF counts obtained over areas of 40,000 to 70,000 km^2 per year. The total area added up to 178,243 km^2 over three years. This is comparable to the total area of, 183,890 km^2 in the 2008 survey.

Table 5 Comparison of EIF Areal Density 2 Periods

	1988-1991		**2008**	
Area in sq.km.	178,243		183,980	
EIF Category	**population**	**density (#/km2)**	**population**	**density (#/km2)**
All EIFs D_{EQUIV} >500m	149	8.4×10^{-4}	99	5.4×10^{-4}
Ice Islands & Fragments II & IIFs D_{EQUIV} >500m	28	1.6×10^{-4}	44	2.4×10^{-4}
MYHFs MYHFs D_{EQUIV} >500m	86	4.8×10^{-4}	55	3.0×10^{-4}
Re-Entrant ice REI D_{EQUIV} >500m	35	2.0×10^{-4}	0	

The areal density of all EIFs in the 2008 survey was about a third less than in the 1988-1991 survey. The density of ice islands detected on 1st August 2008 was greater due to massive calving from the ice shelves just days before the survey. The population of ice islands was greater in late August 2008 because another series of calvings took place. In particular the entire Markham ice shelf became free of its inlet and drifted into the polar pack ice. Note that the database described in this paper does not include the ice islands resulting from the break-up of the Markham ice shelf later in August 2008. The density of MYHFs was less in 2008 than in 1988-91. A significant portion of the 1988-91 data set comprised Re-entrant ice. None were detected in the drifting pack ice in the 2008 imagery.

CONCLUSIONS

An area of 183,890 km2 of the polar pack adjacent to the western coast of the Arctic Islands was surveyed by radar imagery on July 31st and August 1st, 2008.

Extreme Ice Features were counted and the areal dimensions of each were measured using GIS. Sub-populations of ice islands, ice island fragments and multi-year hummock fields were also identified, counted and measured.

For EIFs with equivalent diameter greater than 500m the median, mean and maximum equivalent diameters were 1.2 km, 1.8 km and 13.8 km respectively.

EIF population on Aug.1st, 2008 was 200, versus 162 detected in 1988-1991. The population with equivalent diameter greater than 500m was 99 in 2008, compared with 149 in 1991.

The population of all ice islands and ice island fragments was 133 in 2008, due to significant calving at the ice shelves prior to the survey. This was a dramatic increase over previous years, but the average size was smaller than in previous years.

The number of MYHFs detected with was 67 in 2008, compared with 86 in 1991.

Statistics of EIF size as analyzed in the early 1980's used a data set of significantly larger features than exist today. More recent data sets derived from instruments of higher resolution suggest that the sizes of EIFs in recent years are smaller on average.

The areal density of all EIFs surveyed on July 31st - August 1st, 2008 was 5.4×10^{-4} per km^2, compared with 8.4×10^{-4} per km^2 averaged for 1988-1991. The 2008 estimate does not include a number of other ice islands released later in August when the Markham ice shelf disintegrated.

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