Pack Ice Thickness Measurements in Nares Strait Collected with Helicopter-borne Electromagnetic-Laser Sensors During August 2013

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Abstract

Prinsenberg, S.J., 2014. Pack ice thickness measurements in Nares Strait collected with helicopter-borne Electromagnetic-Laser sensors during August 2013. Can. Tech. Rep. Hydrogr. Ocean Sci. 301: vi+37pp.

As part of the ArcticNet summer survey in the Canadian Arctic using the CCGS Amundsen, ice property data were collected with helicopter-borne Electromagnetic-Laser sensors during August, 2013 along helicopter flight paths from the pack ice in northern Nares Strait (Kennedy Channel). Since pack ice conditions were light in the Channel, the CCGS Amundsen could make its way north to the entrance of the Petermann Glacier's fjord which was entered on August 22 and explored to the Glacier's front.

The pack ice in Kennedy Channel was surveyed on August 21, 23 and 24. It consisted of old First-Year Ice (FYI) and thick Multi-Year Ice (MYI) floes which were either floating freely or embedded in large composite FY-MY ice floes. Measurements indicated that ice floes greater than 100m in width had a mean ice thickness of 2.95m. Of these 140 identified floes, half were composite FY-MY ice, 1/6 FYI and 1/3 MYI. When brash ice (<2m across) was included in the mean thickness calculations, the thickness of the pack ice reduced to a mean of 1.94m (modal 1.78m), ranging among the five transects across Kennedy Channel from 1.75m to 2.2m (modal 1.75m and 1.99m respectively).

The ice concentrations along the five transects ranged from 51.8% to 81.0%, with a mean of 66.8% and covered up to 23.6km or 71.5% of the mean width of the Channel. Eliminating the open water within the pack ice, the ice covered only 53% of the mean width of the five transects. Using 1.2km survey sections, ice concentrations of the surveyed pack ice were as low as 30%.

The mean cross-sectional ice area of the five transects surveyed was $3.33x10^4m^2$, which with a ice drift rate of 20cm/s gave a snapshot ice flux of $5.8x10^{-2}km^3$/day (6.7mSv) leaving Kennedy Channel at the end of August 2013. This is similar in magnitude but lower than the ice fluxes over the mobile ice season entering Kennedy Channel from the Arctic of $6.9x10^{-2}km^3$/day as found by Kwok (2005) for the mean for 1996-2002 and the range of $8.13x10^{-2}km^3$/day to 71.3x10-2km3/day found by Kwok et al., (2010) for the yearly means for 1997-2009.

Résumé

Prinsenberg, S.J., 2014. Mesures de l'épaisseur de la banquise dans le détroit de Nares effectuées durant le mois d'août 2013 au moyen de capteurs électromagnétiques lasers héliportés. Can. Tech. Rep. Hydrogr. Ocean Sci. 301: vi+37pp.

Dans le cadre du relevé d'été mené par ArcticNet dans l'Arctique canadien à l'aide du *NGCC Amundsen*, des données ont été recueillies sur les propriétés de la banquise dans le Nord du détroit de Nares (passage Kennedy) durant le mois d'août 2013, au moyen de capteurs électromagnétiques lasers héliportés, le long des trajectoires de vol de l'hélicoptère. Étant donné que la banquise était peu épaisse dans le passage, le *NGCC Amundsen* a pu faire route vers le nord jusqu'au fjord du glacier Petermann, dans lequel il est entré le 22 août, et qu'il a exploré jusqu'au front du glacier.

La banquise dans le passage Kennedy a été étudiée les 21, 23 et 24 août. Elle était constituée de vieux floes de glace de première année et d'épais floes de glace de plusieurs années flottant librement ou incorporés en grands agrégats de floes de glaces de première année et de glaces de plusieurs années. Les mesures ont indiqué que l'épaisseur moyenne de la glace des floes de plus de 100 m de largeur était de 2,95 m. Sur les 140 floes recensés, la moitié étaient des floes de glace de première année et de glace de plusieurs années agrégées, 1/6 étaient des floes de glace de première année et 1/3 étaient des floes de glace de plusieurs années. Lorsque les sarrasins (épaisseur inférieure à 2 m dans l'ensemble) ont été inclus dans les calculs de l'épaisseur moyenne, l'épaisseur de la banquise a diminué jusqu'à une moyenne de 1,94 m (épaisseur modale de 1,78 m), variant de 1,75 m à 2,2 m (épaisseurs modales de 1,75 m et 1,99 m respectivement) entre les cinq transects du passage Kennedy.

Les concentrations des glaces le long des cinq transects variaient de 51,8 % à 81,0 %, avec une moyenne de 66,8 %, couvrant jusqu'à 23,6 km ou 71,5 % de la largeur moyenne du passage. En éliminant l'eau libre dans la banquise, la glace ne couvrait que 53 % de la largeur moyenne des cinq transects. En utilisant des sections de relevés de 1,2 km, les concentrations des glaces de la banquise étudiée atteignaient seulement 30 %.

La section transversale moyenne de glace des cinq transects étudiés était de 3,33 x $10^4 m^2$, ce qui, avec un taux de dérive de la glace de 20 cm/s, a permis d'estimer le flux de glace quittant le passage Kennedy à la fin du mois d'août 2013 à 5,8 x$10^{-2} km^3$/jour (6,7 mSv). Ce flux est légèrement inférieur aux flux de glace qui entrent dans le passage Kennedy au cours de la saison des glaces mobiles en provenance de l'Arctique à raison de 6,9 x $10^{-2} km^3$/jour observés par Kwok (2005) pour la moyenne de la période de 1996 à 2002 et variant de 8,13 x $10^{-2} km^3$/jour à 71,3 x $10^{-2} km^3$/jour tel que déterminé par Kwok *et al.* (2010) pour les moyennes annuelles de 1997 à 2009.

Introduction

ArcticNet is a consortium of Canadian University researchers, who annually plan and run oceanographic and ice surveys in the Canadian Arctic using the specially equipped Canadian Coast Guard (CCG) icebreaker, “CCGS Amundsen”. The 10- to 12-week cruise is split up in Legs of 3-weeks during which scientists can board and depart from the icebreaker, or stay for 6-weeks and join the large CCG ship’s crew change. There is stiff competition between the 40-or-so onboard scientists not only for room on the research icebreaker but also for allocation of ship’s time and ship’s location to collect data samples. For the summer 2013, a sea ice program was planned as part of the open water sampling during Leg 1b in Northern Baffin Bay. This report describes the ice property data collected in Nares Strait with helicopter-borne sensors during Leg 1b which started in Pond Inlet on August 12 and ended in Resolute Bay on September 5.

Survey

In addition to the open water station work of the ArcticNet Leg 1b survey plan in Northern Baffin Bay (Fig. 1), ice research was planned to take place along the edge of the pack ice in Northern Baffin Bay. Normally an ice tongue would be present along the Canadian side of Northern Baffin Bay and the sea ice research plan was to sample across the ice tongue before and after a storm to investigate how storms and the long-period waves generated by the storms affect the pack ice edge properties. This ice sampling would interrupt the open water station work for a few days before the station sampling would continue.

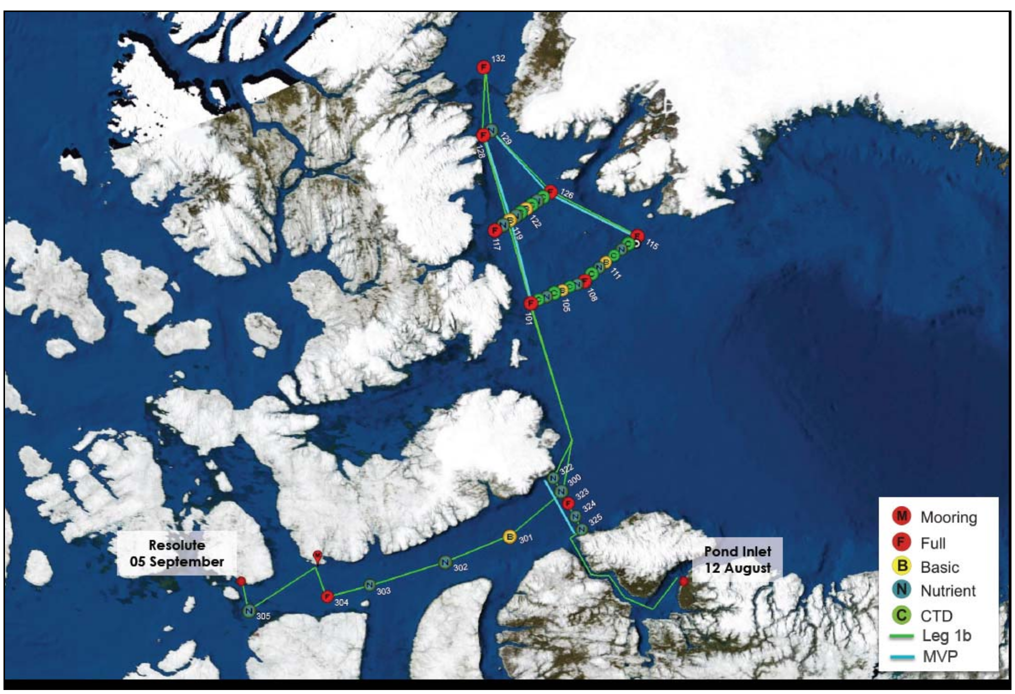


Fig. 1 ArcticNet 2013 Leg 1b station map and planned ship track.

As it turned out, no such ice tongue was present during the last two weeks in August of 2013 in northern Baffin Bay where long period storms waves could be generated and affect the ice edge. Instead the ice work concentrated on the pack ice conditions and ice drift (with ice beacons) north of 80°N in Nares Strait. Nares Strait is one of the three major channels in the Canadian Arctic Archipelago through which ocean and pack ice fluxes from the Arctic Ocean enter the Atlantic Ocean via Baffin Bay (Rabe et al., 2012). Since the pack ice conditions within the northern part of Nares Strait (called Kennedy Channel) were light along the Greenland side of the Kennedy Channel (Fig. 3), the CCGS Amundsen could transect at full speed to the Petermann Glacier (Fig. 2). The CCGS Amundsen transected the open (unchartered) waters of the Petermann's Fjord on August 22 right up to the Glacier's front.

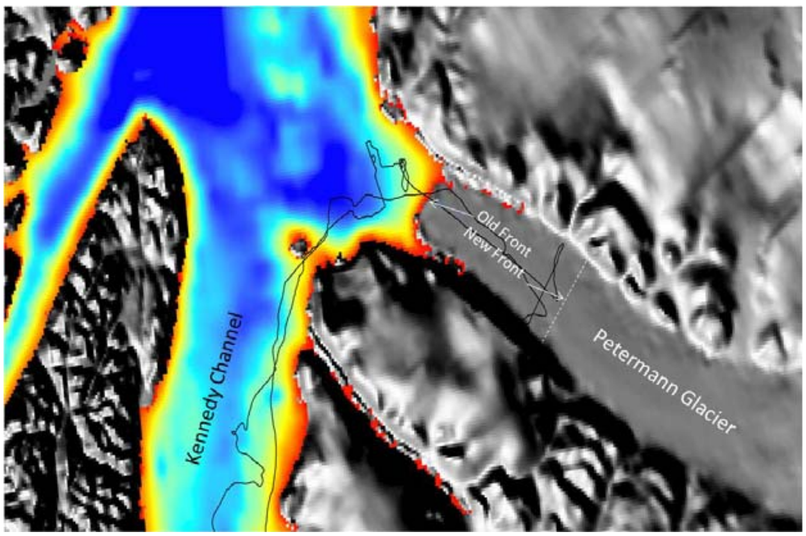


Fig. 2 Image of existing hydrographic data (coloured) mapped to the old Glacier's front along with CCGS Amundsen ship tracks along the Greenland side of Kennedy Channel and tracks in and out of the Petermann's Fjord in unchartered waters. Image is 250km x 150km and centred at 81°N and 63°W (Courtesy of Ian Church, Univ. of New Brunswick).

During the transits to and from the Peterman Glacier, helicopter-borne sensors (Prinsenberg et al., 2002) were used to collect ice properties along helicopter flight paths across Kennedy Channel. Ice thickness, ice roughness and bulk ice conductivity data were collected with an Electromagnetic-Laser system during low-flying survey sections and video-laser data were collected during high altitude survey sections. In addition three satellite-tracked ice beacons were deployed on the pack ice to monitor the pack ice drift in Kennedy Channel. Another 15 ice beacons were deployed by personnel of the Centre of Earth Observation Sciences (CEOS) of the University of Manitoba on ice hazards (small and large tabular icebergs) in Northern Baffin Bay to study the drift response of ice hazards to wind and ocean current forcing.

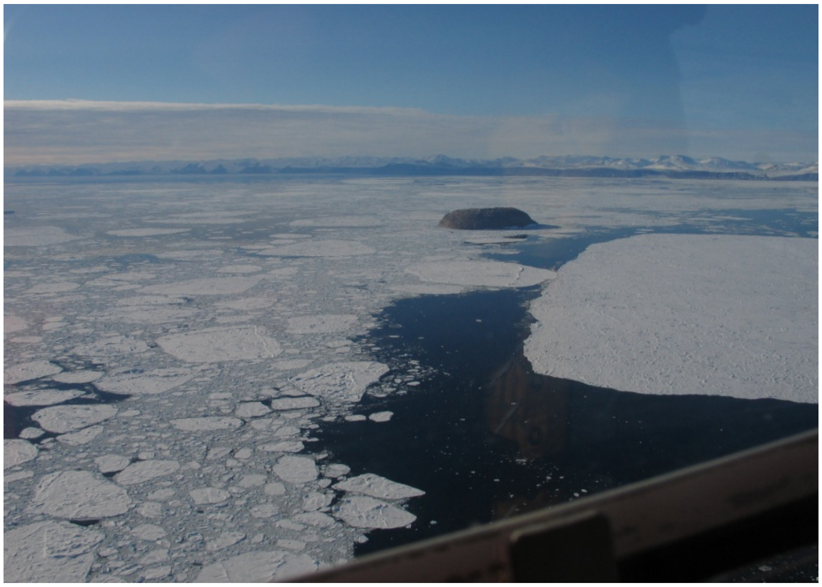


Fig. 3 Ice floes and brash ice (<2m across) in northern Kennedy Channel looking southwest to the Canadian shore on August 20. The island in the picture is west of the entrance to the Petermann Glacier, its location can be seen in Figure 2.

On completion of the water sampling in northern Baffin Bay and deployment of ice beacons on ice hazards by CEOS personnel, the CCGS Amundsen moved into Lancaster Sound where water sampling work continued en route to Resolute Bay for the planned crew change on September 5. Two days of ice work was done on First Year Ice (FYI) floes north of Peel Sound just southwest of Resolute, while waiting for the crew change to occur. On one floe the Electromagnetic sled (Prinsenberg and Holladay, 2009) was towed around in a big triangle by the “Skippy boat” (Fig. 4) and provided accurate ice thickness data over 3 km track length while the floe was drifting 300 m towards the northwest.

Fig. 4 Electromagnetic-GPS sled ready to be towed by the Skippy boat over a floe north of Peel Sound along which the Amundsen was stationed on September 1.

Data collection

The CCG BO105 helicopter stationed on board the CCGS Amundsen was used during the northern section of the ArcticNet 1b leg to measure the ice thickness along flight paths across Kennedy Channel. The measurements were collected with a helicopter-borne Electromagnetic-Laser (EM) system used since the early 2000's and described in Prinsenberg et al. (2002). Due to EM large footprint (diameter), the EM-Laser sensors provides spatial averaged ice thicknesses not specific point samples as obtained by measurements through ice auger holes. The footprint over which the EM-Laser thickness is averaged is three times the height of the sensor above the ocean surface layer, which for two meter thick ice and a flying height of eight meters equals 30m (Kovaks et al., 1995 and Reid et al., 2006). Similarly, the bulk ice conductivity is an average over the EM footprint.

Excellent low level flying by CCG pilot Guillaume Carpentier and the careful moving of equipment on and off the helicopter by CCG Engineer David Gauvin ensured that high quality data were collected throughout the survey. The main collection of EM-Laser ice thickness data was done on three days between August 21 and August 24 (Table 1). Ice beacons were deployed on thick ice floes during this period to monitor the ice drift of the floes within Kennedy Channel. From the two data sets a snapshot ice flux through Kennedy Channel will be estimated. Video data along flight tracks were also collected during high altitude sections of the flight paths.

Table 1 List of EM-Laser and Video data files collected from the pack ice in Kennedy Channel. Station (Stn.) numbers refer to the water sampling station numbers shown in Figure 1 and ice stations added during the survey.

Date/morning (M) or afternoon (A)	Stn./Area	EM file number	Length (~km)	Video files
Aug. 14/A	322-101	Test FEM13003	1	226F136
Aug. 20/A	Stranded Ice island	Laser FEM13004	30	232F137-141
Aug. 21/M	N of Hans Isl.	FEM13006	170	233F142-147
Aug. 21/A	N of Hans Isl. + Reco	FEM13007	30	233F148-154
Aug. 21/A	N Hans Isl. to 250	FEM13009	120	233F155-159
Aug. 23/A	Hans Isl. stn. 252	FEM13011	42	235160-161
Aug. 23/A	N of Hans Isl. stn. 252	FEM13012	64	235162
Aug. 23/A	N of Hans Isl. beacons	FEM13013	---	235F163
Aug. 23/A	Video floe stn. 252	FEM13013	---	235F164
Aug. 24/A	S Kennedy Channel	FEM13016	41	236F165
Aug. 24/A	S Kennedy Channel.	FEM13017	41	236F167-168

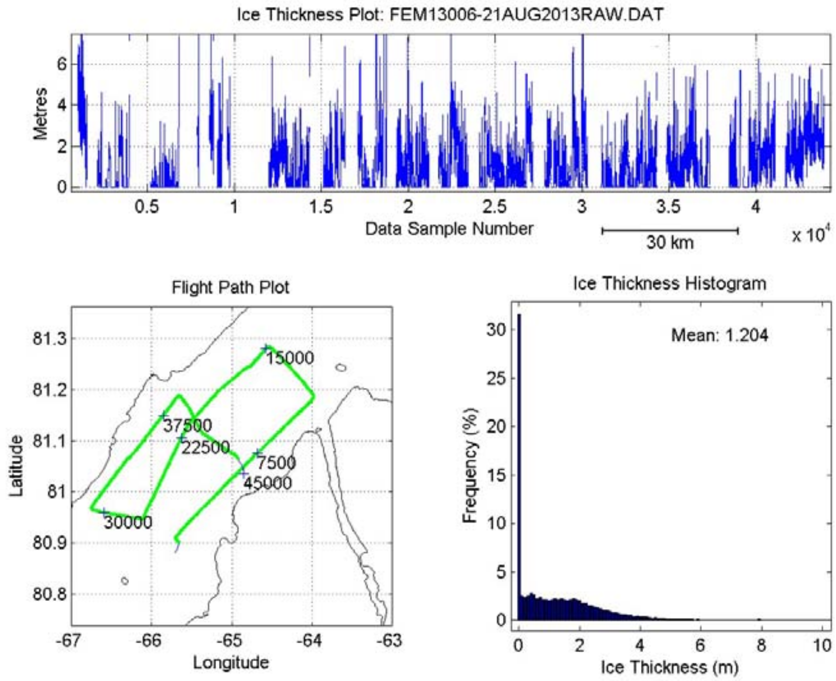


Fig. 5 Flight track and ice thickness profile data from northern Kennedy Channel while the Amundsen traversed along the Greenland side of the Channel on August 21. CCGS Amundsen position is at data sample point 45000.

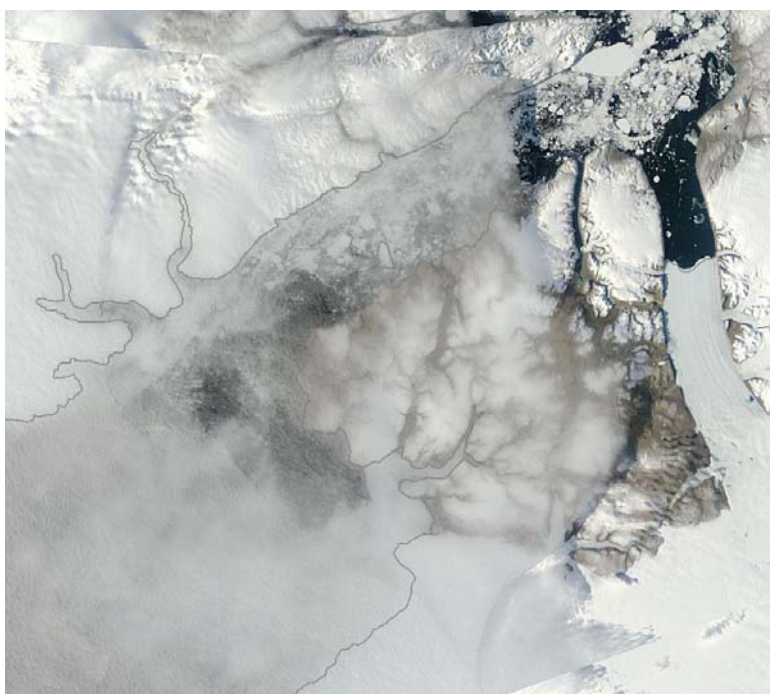


Fig. 6 MODIS composite image of August 21, cloud free condition in the Peterman Glacier area (right/top corner) while the pack ice mainly along the Canadian shore can just be seen below the light cloud cover in Kennedy Channel. The image is 250km x 250km and centred at 80.5^{o}N and 66^{o}W.

The data in the northern part of Kennedy Channel shown in Figure 5 were collected on August 21, the day before entering the Peterman Glacier's fjord, while the CCGS Amundsen was transiting from Hans Island to the Glacier. Its total flight covered a distance of 170km (Fig. 5). The mean ice thickness along the total flight track including open water areas (32%) was 1.2m. Most of the open water areas occurred along the first section of the flight track off the Greenland coast where the Amundsen was transiting towards the Glacier (Fig. 6). Excluding the 32% of open water areas, the mean ice-only thickness of the ice floes and brash ice along the track increases to 1.78m. Even this mean ice-only thickness value includes a lot of thin ice composed of small ice floes and brash ice and thus open water areas that are smaller in widths than the 30m EM footprint.

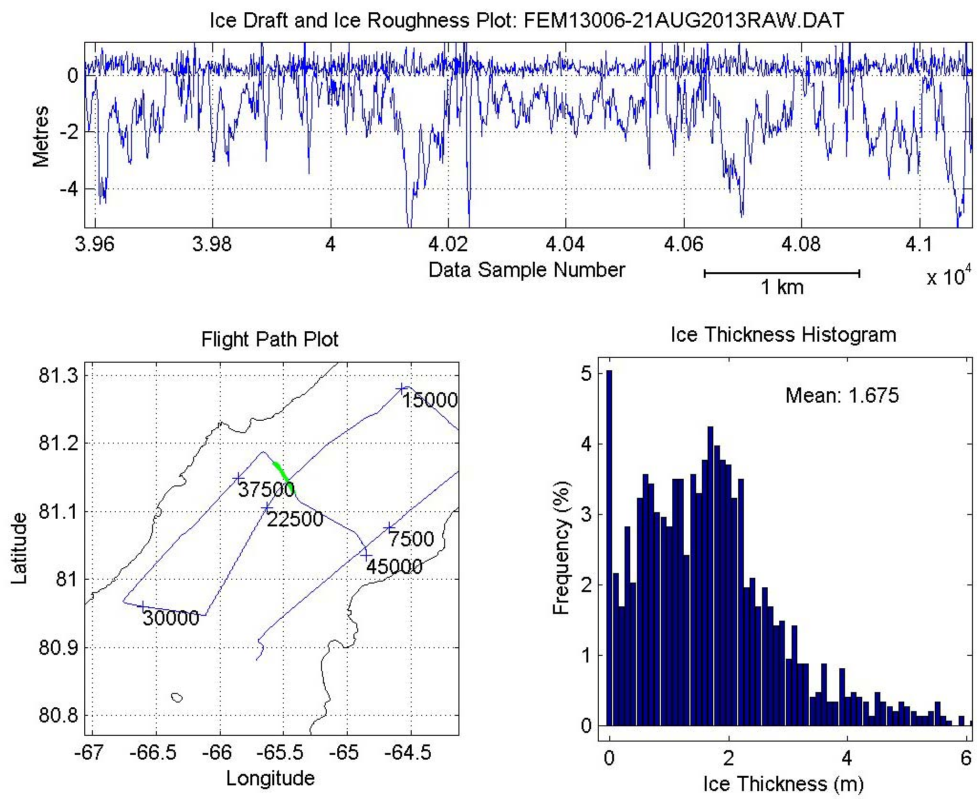


Fig. 7 Ice thickness profile of a 5.5 km line section that has about 7 floes of more than a ½ km in length. Open water regions between these densely packed floes still amount to 5% of the total profile length.

A small 5.5 km section of this data across Kennedy Channel collected while the helicopter was on the way back to the CCGS Amundsen is shown in Figure 7. In the top panel the laser data are plotted upwards and shows the pack ice surface roughness, while the EM data is plotted downwards and shows the keel depths averaged over the 30m footprint of the EM sensor. This data section (Fig. 7) shows that large ice floes with widths of 0.5 to 1.0 km do occur, as were seen in the photograph (Fig. 3), but much of the pack ice consisted of smaller floes and brash ice. Four of the thicker ice sections reach keel depths of 4m (averaged over 30m distance). Open water regions of 30m or wider between these densely packed floes still amount to 5% of the total profile length shown; indicating the pack ice was not under internal ice pressure as reflected by the ease the

CCGS Amundsen could transit through the pack ice. At the locations of the deep keels the bulk ice conductivity (Fig. 8) reach minimum values of 0.001S/m indicating that most salt has been flushed out during snow melt cycles, a property of Multi Year (MY) ice. The next winter season had already started as melt ponds within the FY ice floes had already refrozen with some covered with new snow, while some melt ponds at the floe edge were still open due ocean heat flux generated from sun radiation input into adjacent open water areas. The pack is thus is in transition from summer to winter conditions. The FYI can be labelled as "old" FYI that already has gone through a melt cycle and snow melt water flushing that reduces the ice conductivity below expected values of FYI of 0.05 to 0.025S/m for 1.0 to 2.0m thick ice (Haas et al., 1997).

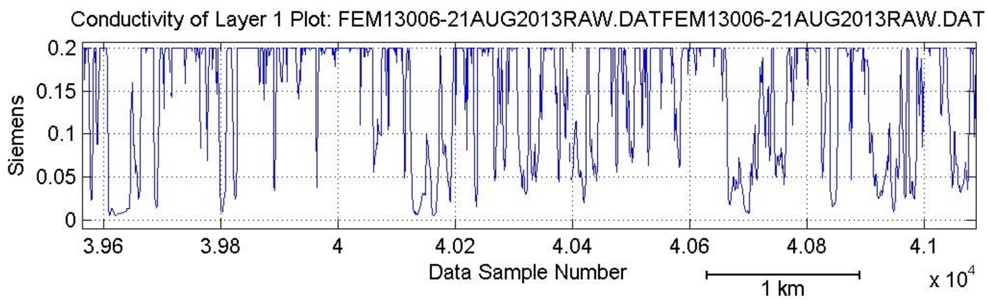


Fig. 8 Bulk ice conductivity for the same ice thickness profile shown in Fig. 7.

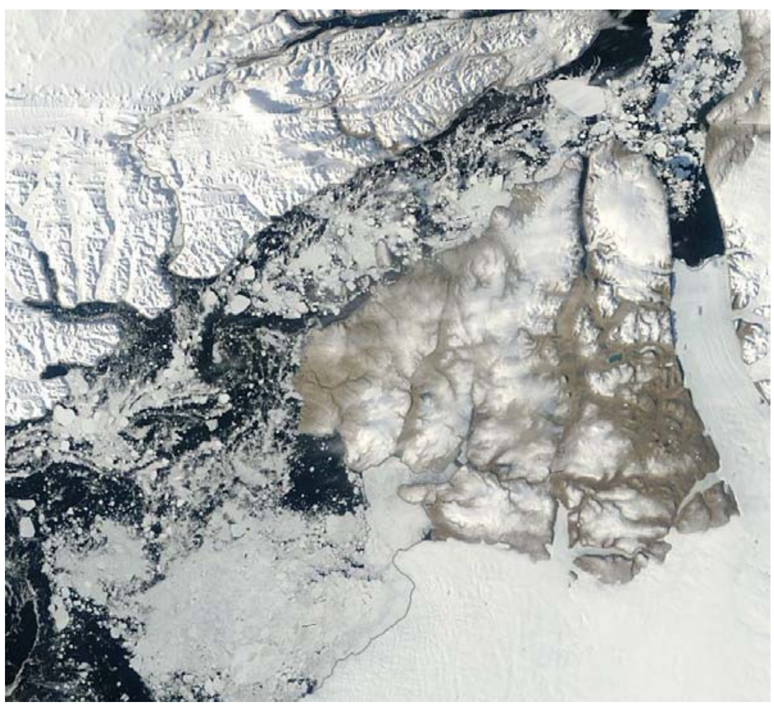


Fig. 9 MODIS Image of August 23 when the CCGS Amundsen was moving south through Kennedy Channel. Much of the pack ice drifted over to the Greenland side of the Channel and slowed down the southward progress of the Amundsen. The image is 250km x 250km and centres at 80.5°N and 66°W.

Fig. 10 On-ice sampling south of Hans Island on August 23.

During the passage south, on-ice sampling was done on August 23 just south of Hans Island (Fig. 10). The helicopter sampled the floe five times and the ice thickness profiles are shown in Figure 11. Since the second group of three profiles (data file FEM13012) were collected one hour after the first two profiles (FEM13011), the GPS positions of the lines shifted relative to the location of the other two lines caused of ice drift and rotation. On the map of Figure 11, the stars at the end of each profile line show the end of the survey pass. It shows that the passes were flown in both directions so that the red and black ice thickness profiles in the top of the figure are reversed in direction relative to the blue, green and turquoise lines. All line sections are about 1½km long.

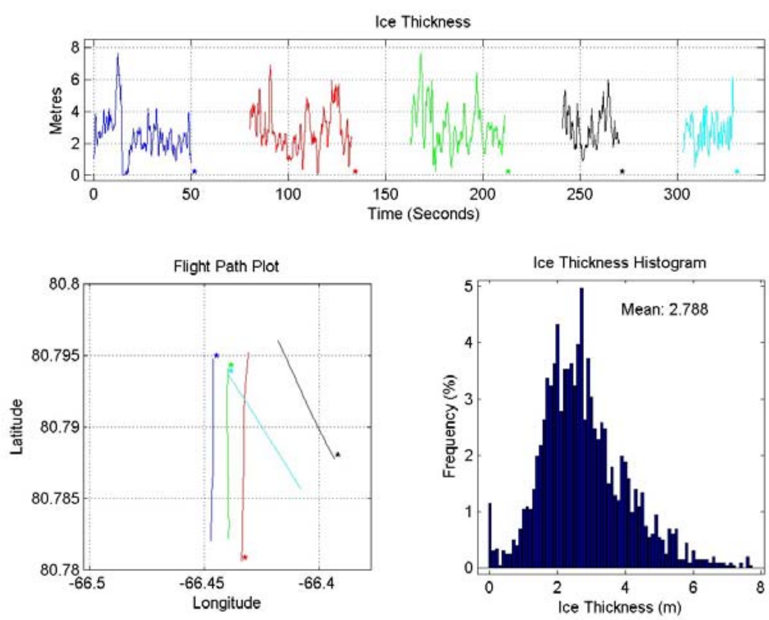


Fig. 11 Five EM-Laser ice thickness passes over sampled ice floe south of Hans Island on August 23.

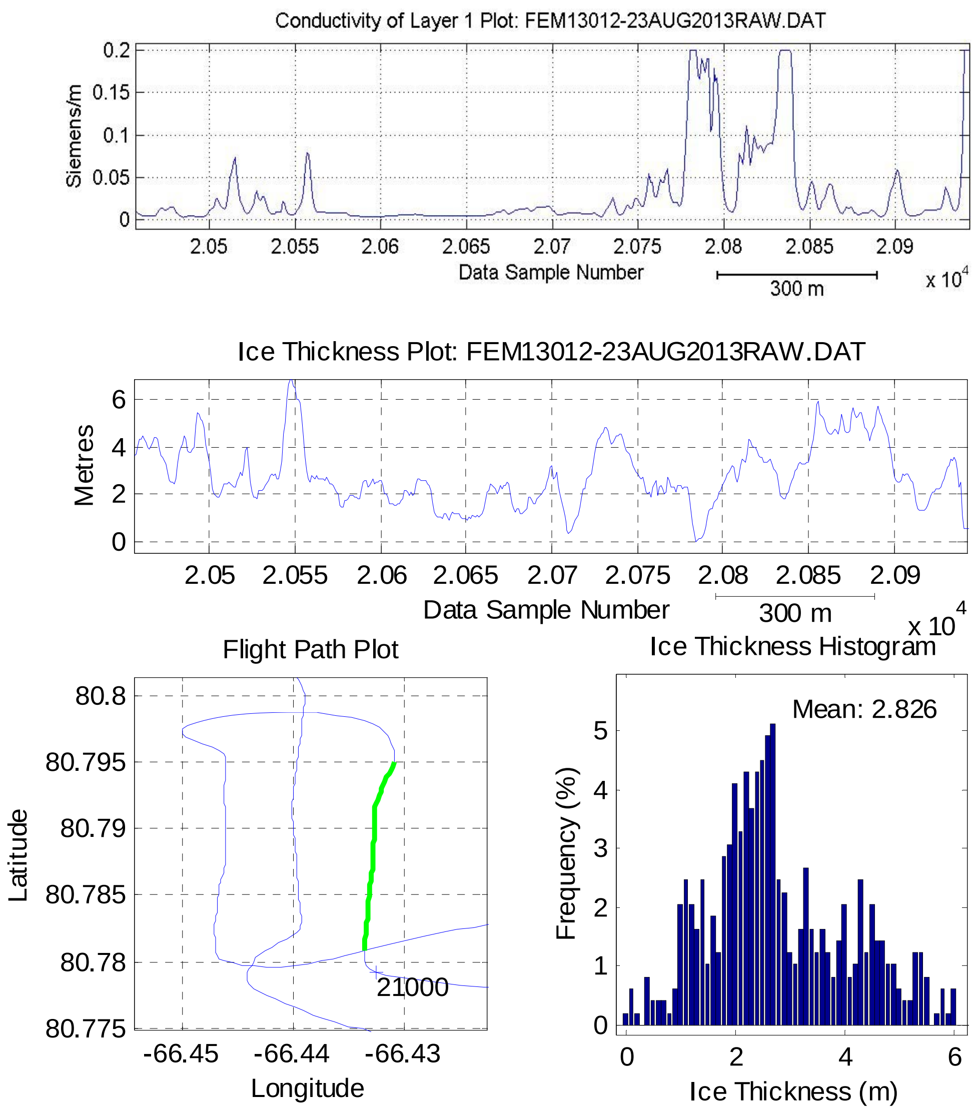


Fig. 12 The bulk ice conductivity and ice thickness profile of just the red line in Fig. 11.

In Figure 12 the ice conductivity and ice thickness profile lines are shown for the red line of Figure 11. The thicker portions (>3m) of the floe are MYI with low ice conductivity. There is a floe section of 200m (data sample numbers 2.075-2.085x10^4) that has high ice conductivity values and a section of zero ice thickness and is thus possibly FYI with leads whose sea water conductivity is 2.5S/m. What is interesting however is the low ice conductivity of the 600m thin ice section between sample numbers 2.055 and 2.075x10^4, by the thickness it is possible old FYI that has lost its salinity content due to snow melt flushing. But on the other hand it can be MYI that has been subjected to a large amount of melting. This is different from the results of Haas et al. (1997), but their data does not include late summer values when the FYI just changed over to second year ice by losing its salinity content.

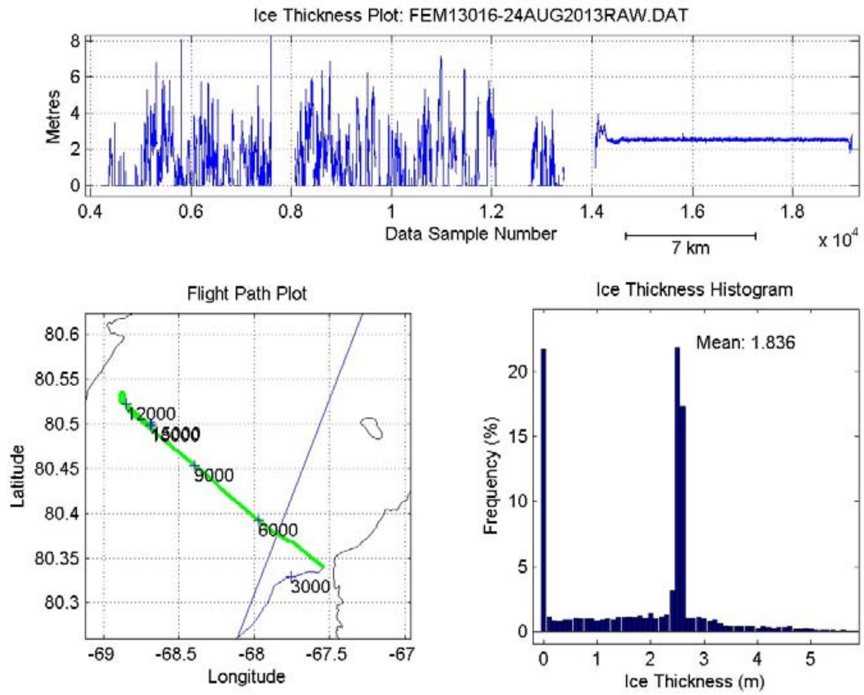


Fig. 13 EM transect across Kennedy Channel just south of Crozier Island (80.5^{o}N). At the end of the ice thickness time series plot the helicopter landed on an ice floe to deploy a satellite-tracked ice beacon; the floe was 2.5m thick and caused the peak in the ice thickness histogram based on time series data.

An additional two transect areas were sampled as the Amundsen moved south through Kennedy Channel; the flight track of the southern transect surveyed is shown in Figure 13 (just south of Crozier Island). The track was flown from SE to NW and an ice beacon was deployed at the end of the line. This deployment is shown by the constant ice thickness section of the time series plot. Here the helicopter sat on the ice while the EM-Laser sensors kept collecting data samples at a rate of 10 per second. The ice thickness where the beacon was deployed was 2.5m thick with high ice conductivity of 0.035S/m (possibly an old ridge made of ice blocks and sea water trapped between them).

A smaller profile section of this data across this southern part of Kennedy Channel is shown in Figure 14. It shows four distinct floes, their keel depths reaching 4-6m where the ice conductivity reaches minimum values, but not as low as expected by Haas et al. (1977) results. The floes are between 300-500m in length with 38% of the line section between the floes ice free. When this open water region is removed from the mean ice thickness calculation (1.73m), the mean ice thickness of only the floes is 2.78m as still some brash ice with leads (high ice conductivity) at the edges of the floes were included in the calculation. This figure shows that one can zoom into the data to find individual floes based on the persistent surface and bottom topographic features. The attached brash ice of each individual floe can be deleted to focus just on floe itself. This will be done later in the report on the total data set in order to answer the question “How thick were the ice floes in Kennedy Channel”, a question an icebreaker captain transecting the area or an Ice Engineers calculating ice forces on ships will want to know.

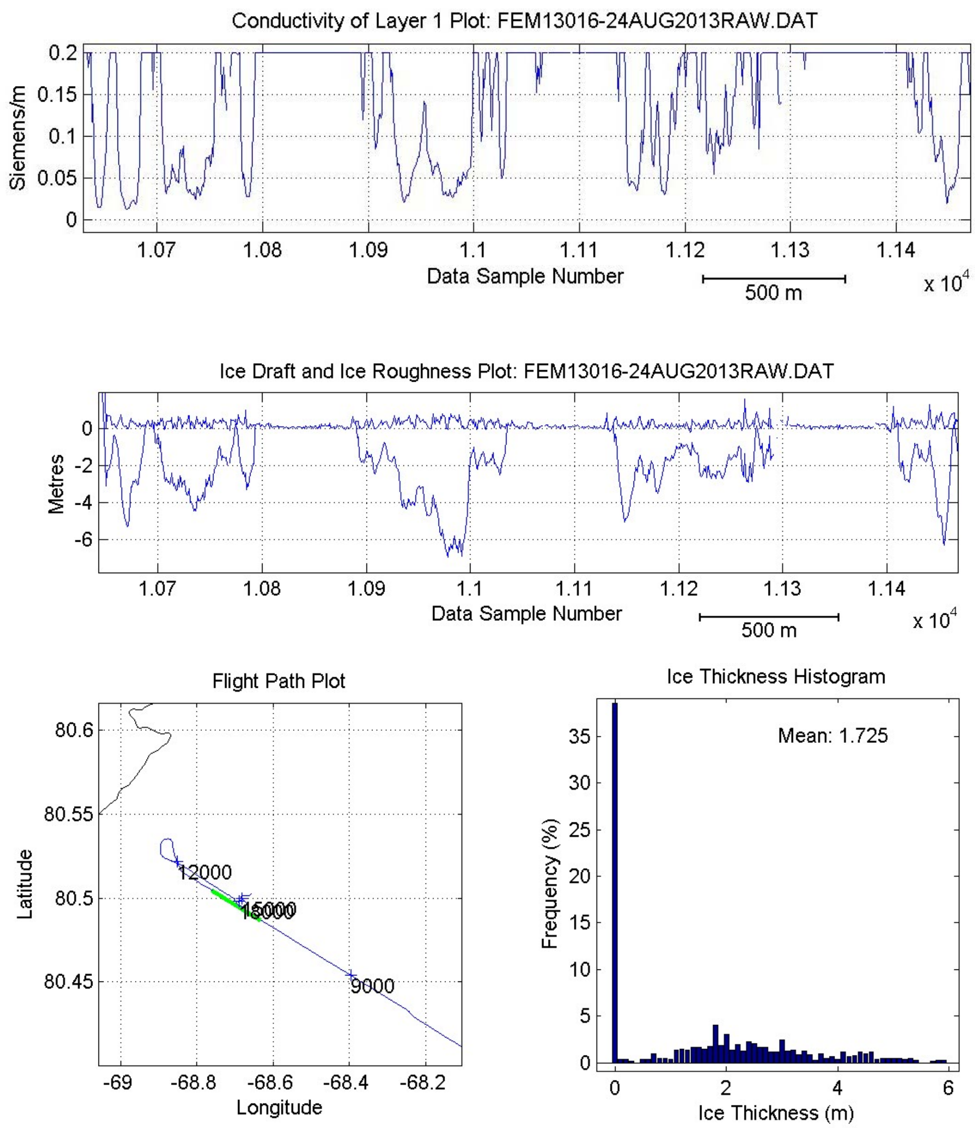
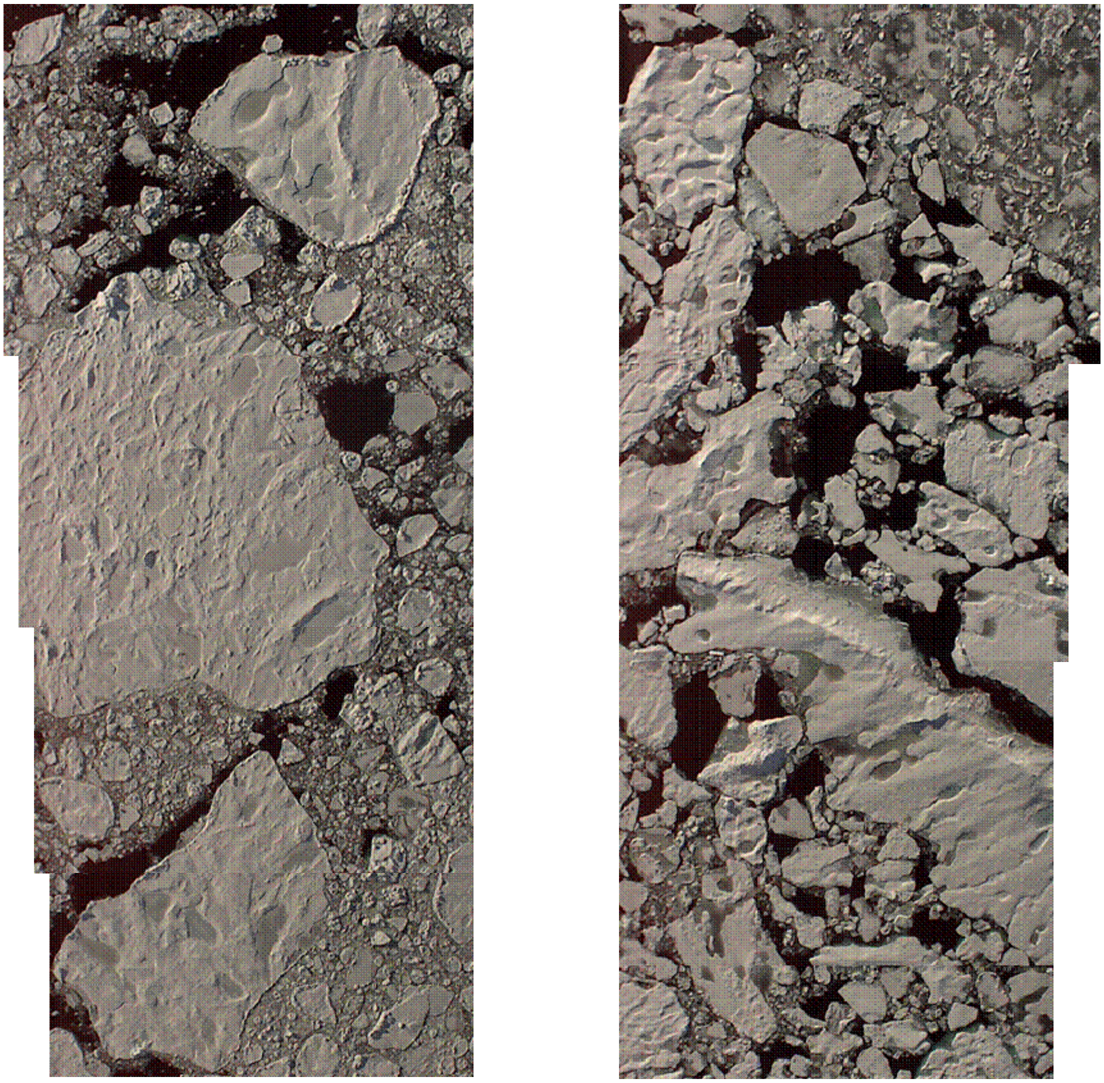


Fig. 14 Four distinct thick ice floes at the end of the ice thickness profile across Kennedy Channel collected on August 24.

Video data were collected during high altitude flight sections to provide a larger spatial coverage of the pack ice than the EM-Laser data provides. The width of the video frame is 1.1 times the height of the helicopter and each frame is frame-grabbed at a calculated sampling rate to provide 40% overlap between successive frames in order to make mosaics. The sampling rate depends on the altitude and ground speed of the helicopter. Samples are shown for the two sides of the southern entrance to Kennedy Channel in Figure 15. They show a mixture of MYI and old FYI floes with some FY brash ice. Melt ponds were already refrozen and some new snow was present on the pack ice. Since the video widths are 1.1 times the height of the helicopter, the width for the mosaic on the left is 216m and for the mosaic on the right 145m.



F167 start frame 81877 at 196m F168 start frame 82668 at 130m

Fig. 15 Examples of video mosaics from the southern part of Kennedy Channel.

Except for deployment of ice beacons on ice hazards, no ice work was done transecting northern Baffin Bay or Lancaster Sound due to the lack of pack ice. Some ice was present west of Resolute Bay and on September 1, a large FY ice floe (2miles x 6miles) north of Peel Sound was sampled for ice thickness with an EM sled towed behind the Skippy boat. Total track length sampled in a triangle was about 1.5km in ¾hour during which time the floe drifted to the NE at about 200m per hour. Figure 16 shows a picture of the EM sled towed by the Skippy boat as it was moving away from the Amundsen and still seen in the background. Figure 17 shows the ice thickness data collected by the EM sled; the ice thickness ranged from 50cm to 150cm with a mean of 1.025cm. The sled was stopped at four places and ice thickness measurements were collected through 2inch auger ice holes and these compared well with the EM sled data.

Fig. 16 EM sled being towed by the “Skippy Boat” over a FYI floe north of Peel Sound on September 1 on a typical overcast day when surface topography is obscured.

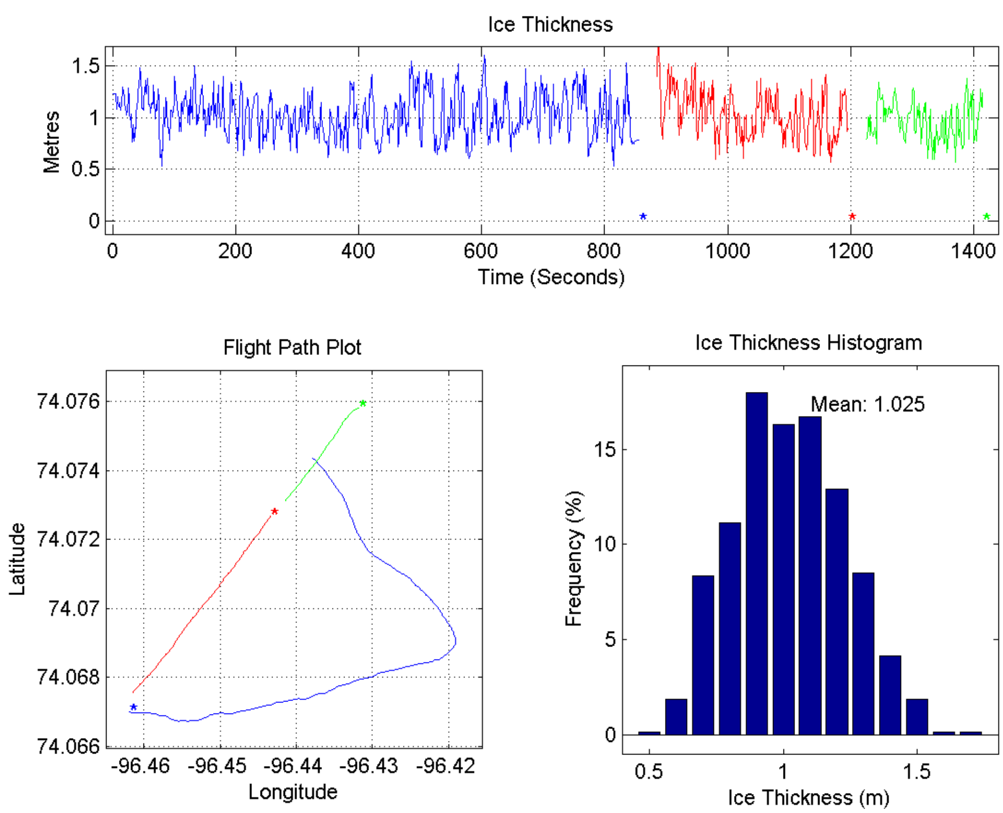


Fig. 17 EM sled data collected on September 1 (Fig. 16) over a FYI floe.

Ice floe thicknesses in Kennedy Channel

As shown in Figure 14, distinct ice floes can be identified within EM-Laser profile data. For the total EM-Laser data set collected in Kennedy Channel, 140 floes larger than 100m were identified and listed in an EXCEL file from which plots were generated. The two largest floes along the path the helicopter flew were 2.7 and 4.2km wide. The large 4.2km floe is shown in Figure 18 and occurred at the end of the profile FEM13006 shown in Figure 5. The CCGS Amundsen actually had to change course to go around (east) of this floe. There may be a smaller floe adjacent to this floe as there is a small open water area (0.0 ice thickness) at data sample point 4.29×10^4 where a small peak in the ice conductivity also occurs. Without direct measurement one can speculate on some of the features in Figure 14: MY ridge (sample 4.3×10^4) with un-consolidated ridge blocks at both ridge sides (high conductivity), old FY ice at sample 4.32 - 4.34×10^4 and FY ridge made of lose ice blocks at sample 4.39×10^4.

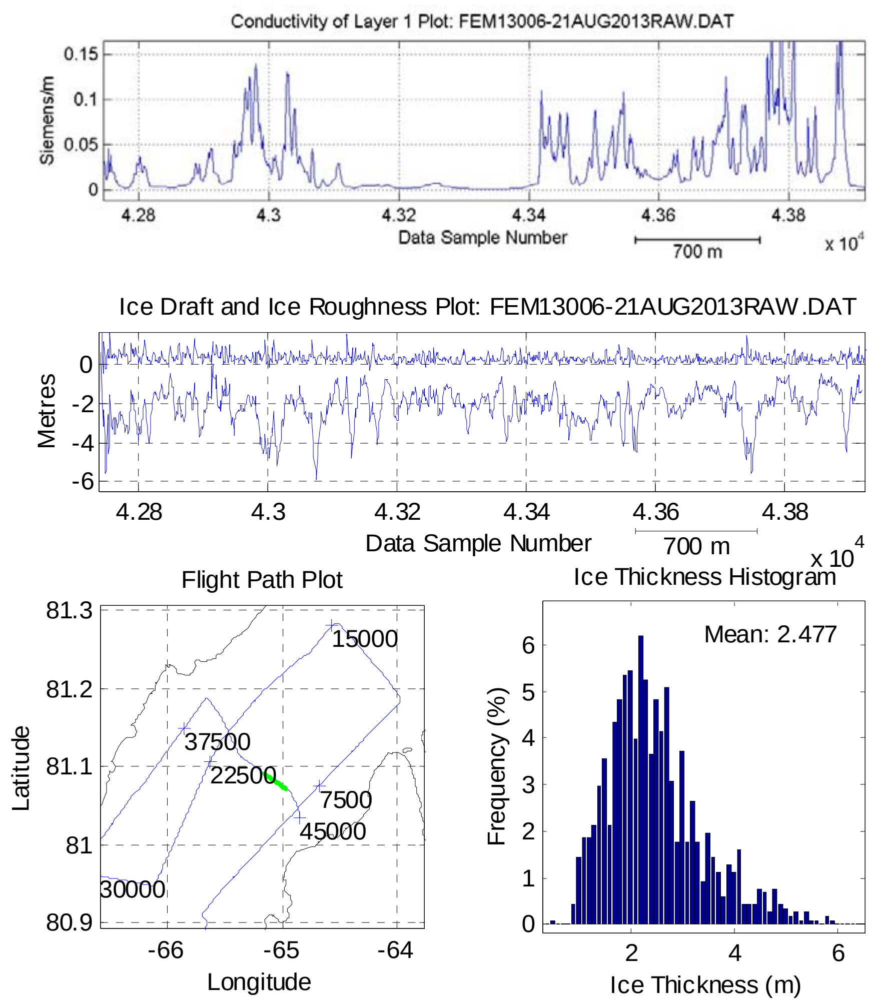


Fig. 18 Large composite ice floe at the end of the EM file 13006 where the helicopter landed on the CCGS Amundsen while the icebreaker moved East around the floe (sample point 45000).

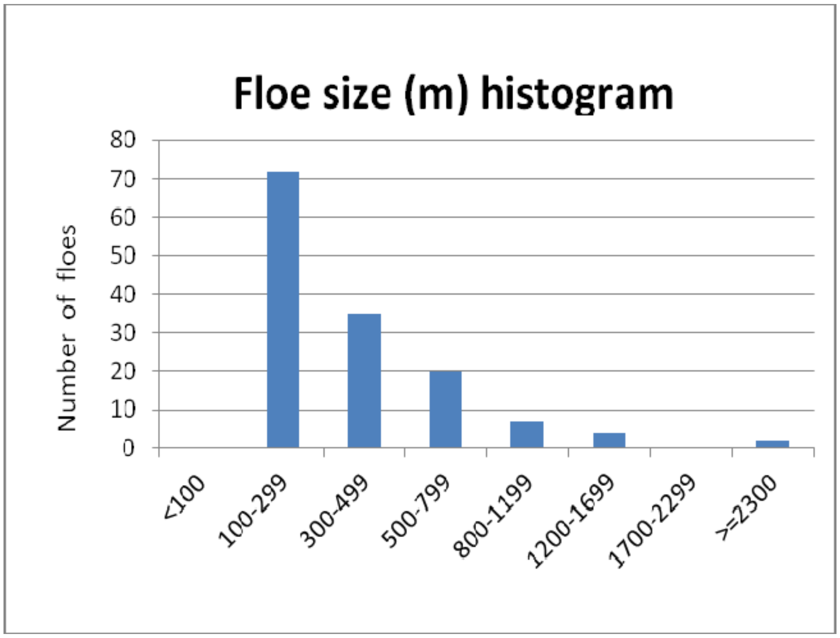


Fig.19 Ice flow size histogram of 140 floes identified to be wider than 100m wide where the flight path crossed the floes within the EM-Laser data from Kennedy Channel.

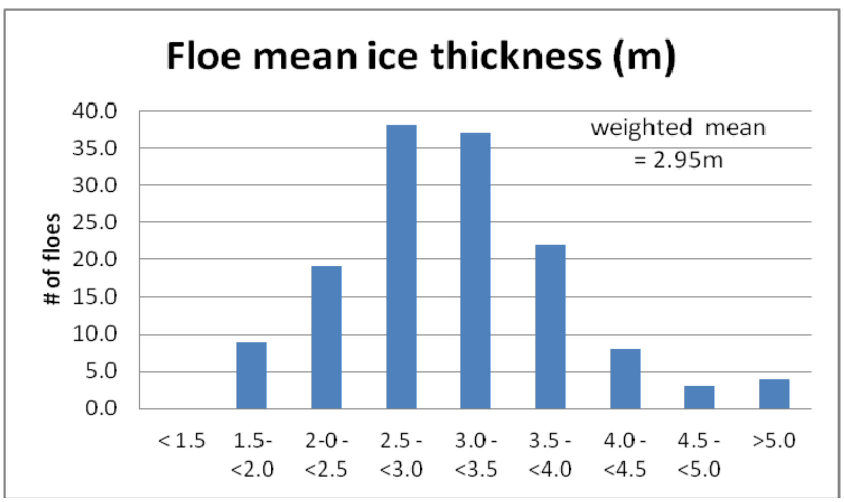


Fig. 20 Histogram of the mean floe ice thicknesses of the 140 floes identified in the data set to be wider than 100m. The weighted mean thickness by width is 2.95m.

The mean ice thickness histogram of the 140 ice floes in Kennedy Channel is shown in Fig. 20; their weighted mean thickness by floe width is 2.95m. The four floes with a mean thickness of >5.0m were 250, 250, 320 and 350m wide where the helicopter passed over the floes. Although it is very subjective to classify a floe as a FY, Composite or MY ice floe; it was done according to their thickness, surface roughness and bulk conductivity for the 140 floes identified and their ice type histogram is shown in Fig. 21. In reality, all floes are composite as some FY ice was always connected to any MY ice fragment. But the floes were classified according to the dominant ice type component. The ice type histogram shows what is expected; the MYI floes are generally the thickest while the FYI floes the thinnest. The composite as expected occupy mostly the middle thicknesses and were the most numerous (67) in contrast to 23 FYI floes and 50 MYI floes. This distribution agrees what was visually seen along the tracks while collecting the data. The mean ice thickness of the FYI floes was 2.4m (modal 2.3m), of the composite FY-MY ice floes was 2.9m (modal 2.9m) and of the MYI floes was 3.6m (modal 3.5m).

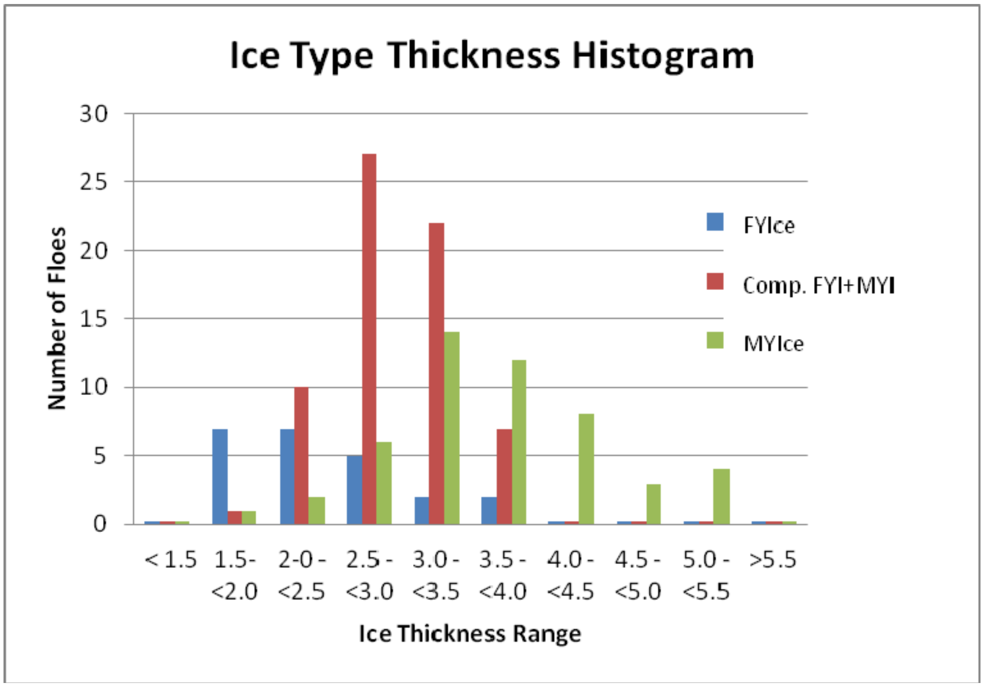


Fig. 21 Ice type thickness histogram of the three types of floes identified within the 140 floes identified in the Kennedy Channel data set.

Ice thickness transects across Kennedy Channel

As part of calculating the ice volume across Kennedy Channel at five locations (transects), the EM ice thickness and laser data were converted from the XML into EXCEL files from which the total sample number along the survey track were determined for possible EM-Laser ice thickness data as well as the actual number of ice thickness samples for ice thicker than 10cm. By dividing the number of actual data points by the number of possible data points the ice concentration along the flight patch was determined. In addition the ice thickness mean and model thickness and cross-sectional ice area were determined. This was done for the five available transects made up seven survey line sections as shown in Figure 22.

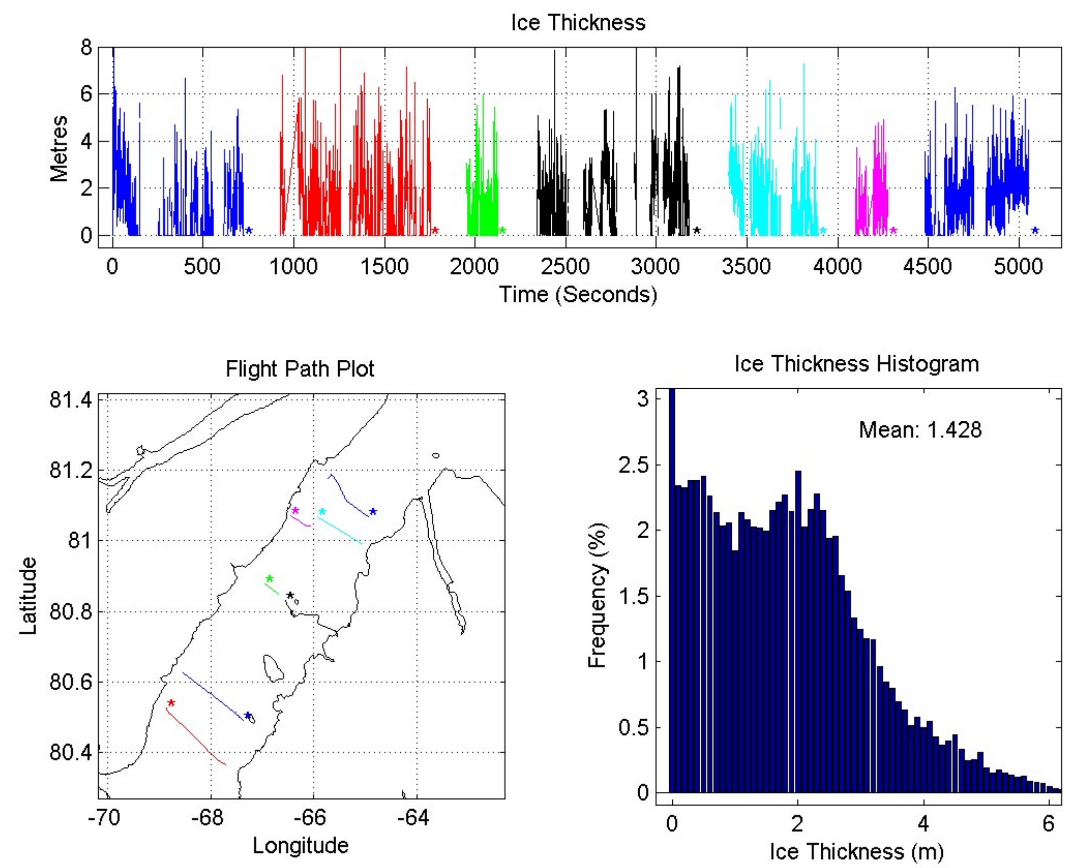


Fig. 22 The seven ice thickness profiles making up the five transects across Kennedy Channel. The 0-10cm ice thickness bin had a frequency value of 25% is not shown in order to expand the bars of the other ice thickness bins.

The plots and results of the five separate transects are shown below and some their results are then summarized in a Table 2. The transects are identified by their mid-transect latitude whose values range from 80.40^{o} North to 81.1^{o} North.

Nares Strait transect 80.40

The profile data for transect 80.40 is located in file FEM13016 and was collected on August 24 while flying from East to West.
The file contains a total of 6700 data points with 6173 laser values and 527 NAN values (Non Available Number) that occurred mostly over open water areas where the Laser signal does not return to the laser receiver. It also includes data collected during the Background section when the EM sensor is re-initialized for possible sensor drift.
The Background was done between sample points 2178 and 2652 or spanned 474 sample values. At these data sample points, no ice data are collected. Therefore we have 6700-474= 6226 possible sample points if perfect ice thickness data set was collected. There are actually 5656 observations with laser data of which a total of 1990 ice values are less than 10cm values and taken as open water areas.
So 5656-1990 = 3666 are ice values of thickness >10cm. Since we could have 6226 ice values but only have 3666 values of ice >10cm, the ice concentration is therefore 3666/6226 = 58.8% along the survey track. Their thickness sum is 8105.869 and thus provides a mean ice thickness of 2.215m. (8105.869/3666=2.215m)

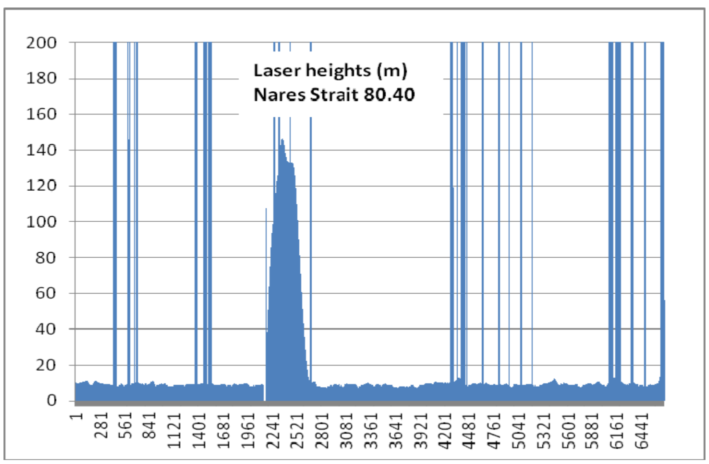


Fig. 23 Time series Laser height profile of Transect 80.40 showing laser spikes and one Background calibration peak.

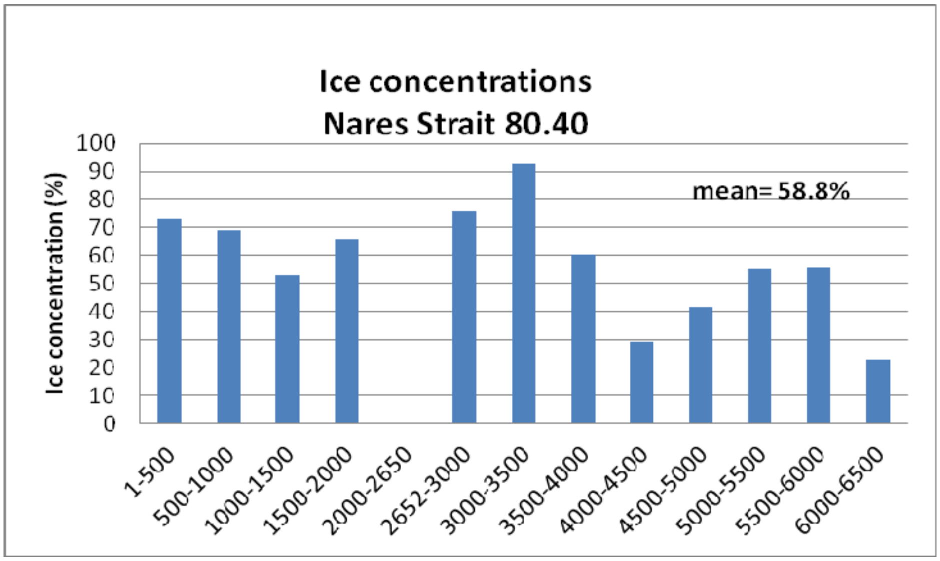


Fig. 24 Subsections' mean ice concentrations for transect 80.40.

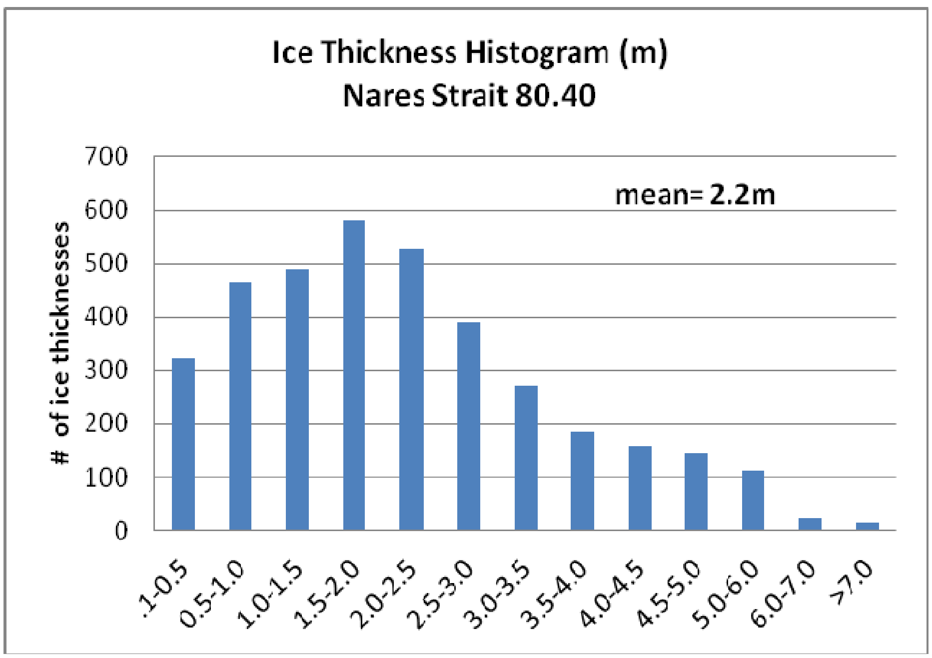


Fig. 25 Ice thickness histogram of transect 80.40 (modal 1.99m).

Nares Strait transect 80.55

The Nares Strait transect data was collected on August 24 while flying from West to East. The profile data is stored as file FEM13017 and consists of 6777 data samples. Two Backgrounds were done along the transect spanning 1418 sample points where no ice data can be collected. So there are 6777-1418= 5359 possible data points for perfect ice data set.

We have 4407 ice thickness samples but with a lot of samples (1663) less than 10cm and these were taken as open water samples. Total ice samples >10cm is 4407-1663=2764. So with 2764 ice samples out of the possible 5359 sample provides an ice concentration of 2764/5359 = 51.8 % and a mean ice thickness of 5456.848/2764= 1.97m where 5456.848 is the ice thickness sum of ice samples >10cm.

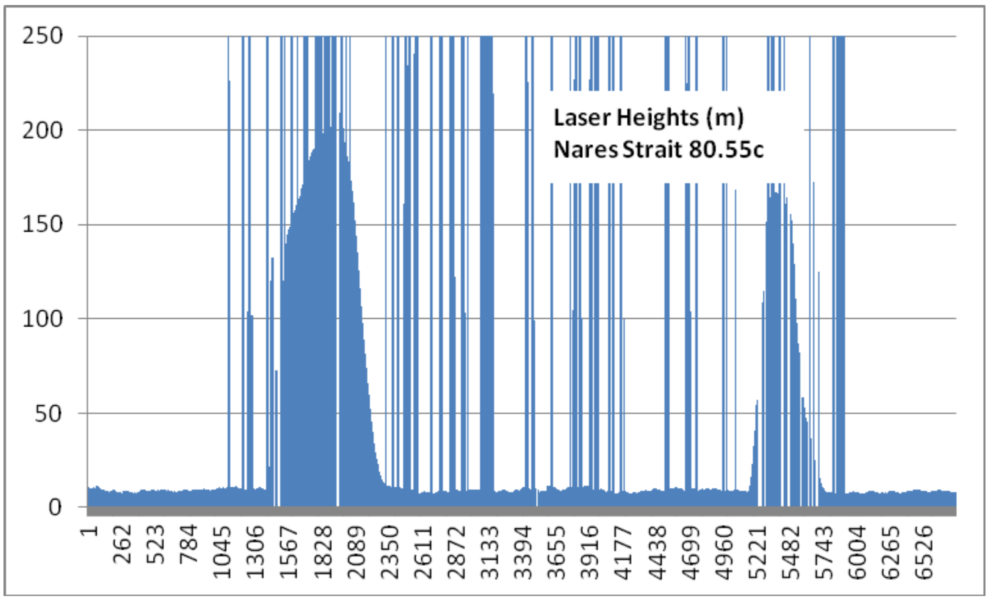


Fig. 26 Time series Laser height profile of Transect 80.55 showing laser spikes and two Background calibration peaks.

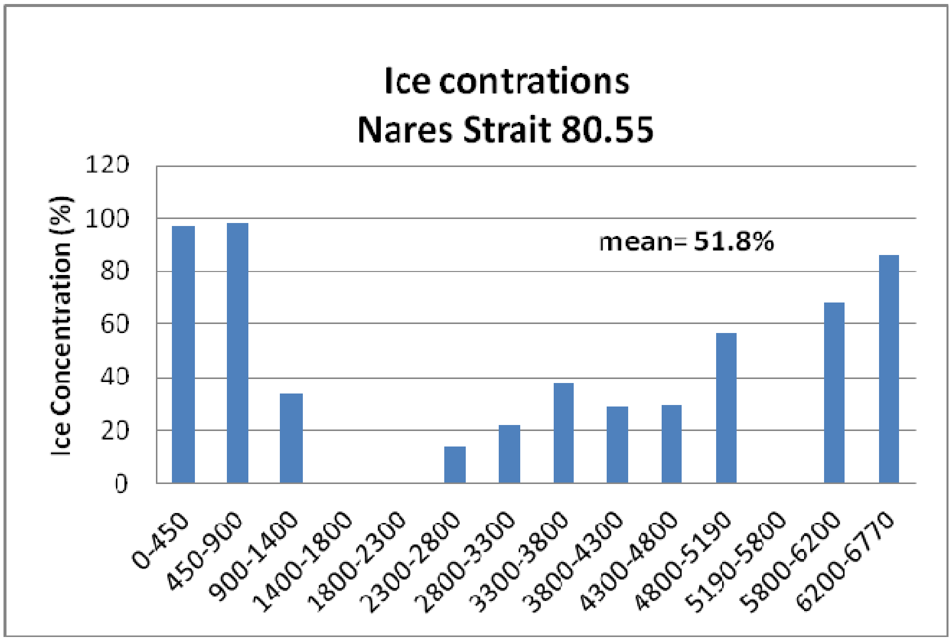


Fig. 27 Subsections' mean ice concentrations for transect 80.55.

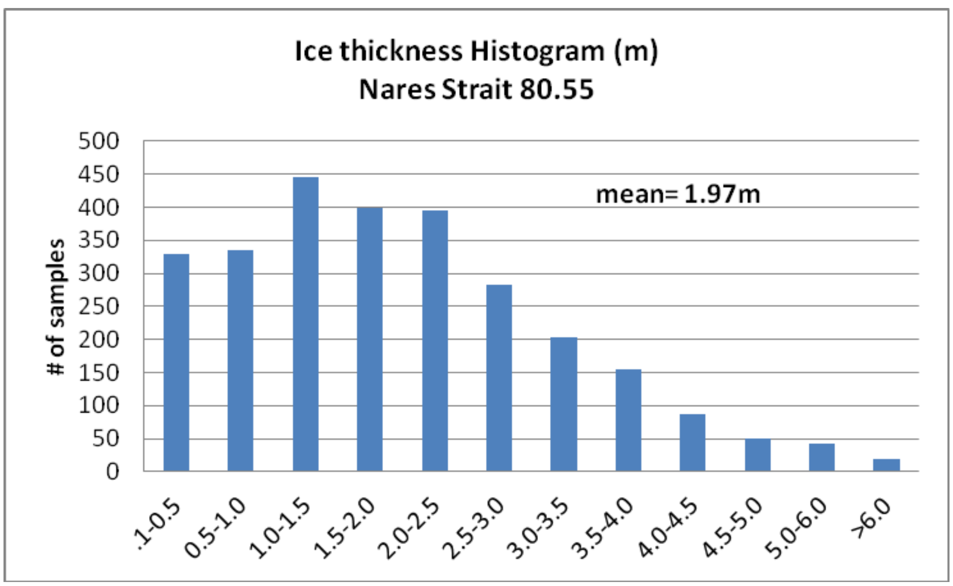


Fig. 28 Ice thickness histogram of transect 80.55 (modal 1.84m).

Nares Strait transect 80.80

Nares Strait 80.80c profile data consists of two FEM data sections, re-arranged so that FEM file 13011 is plotted first and goes from 65.889^{o} to 66.4^{o} W and then FEM file 13012 continues from 66.68^{o} to 66.9^{o} W. Both data sets were collected on August 23 while flying East to West.
There are 6014 possible data points but 4195 points had ice thicknesses >10cm so that the ice concentration is 4195/6014= 69.8%. One large lead was over-flown at 15m at the time sample number 1400.
The sum of the ice thicknesses >10cm = 7473.618 for the 4195 samples which gives an ice thickness mean of 7473.618/4195 = 1.78m.

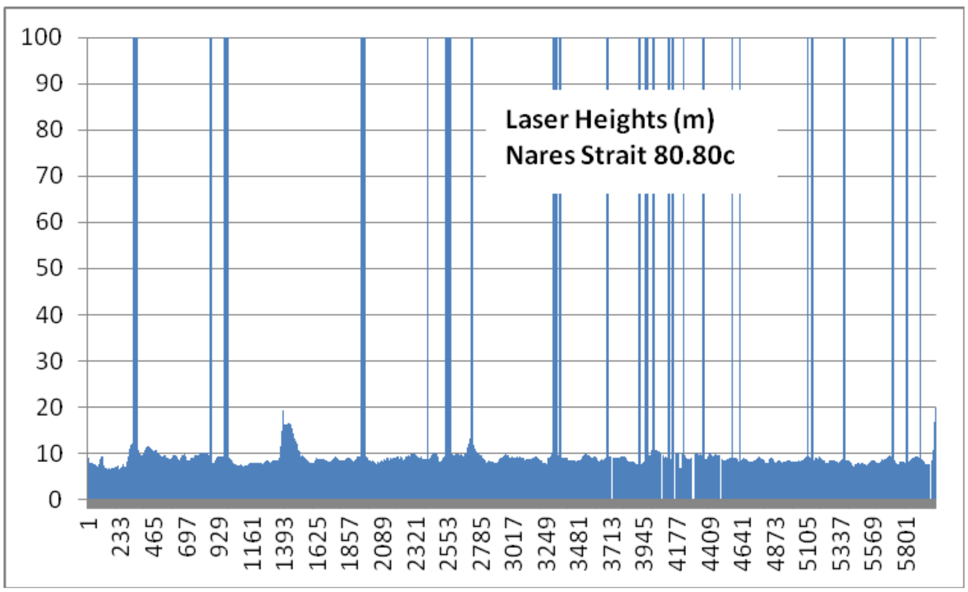


Fig. 29 Time series Laser height profile of Transect 80.80 showing laser spikes and one 15m high laser peak where the helicopter increased its altitude while passing over a wide lead.

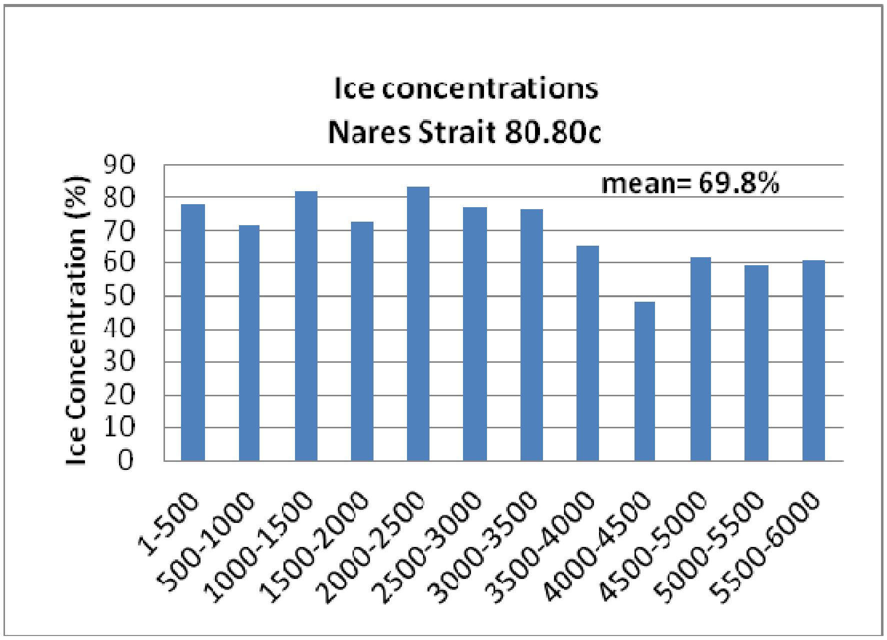


Fig. 30 Subsections' mean ice concentrations for transect 80.80.

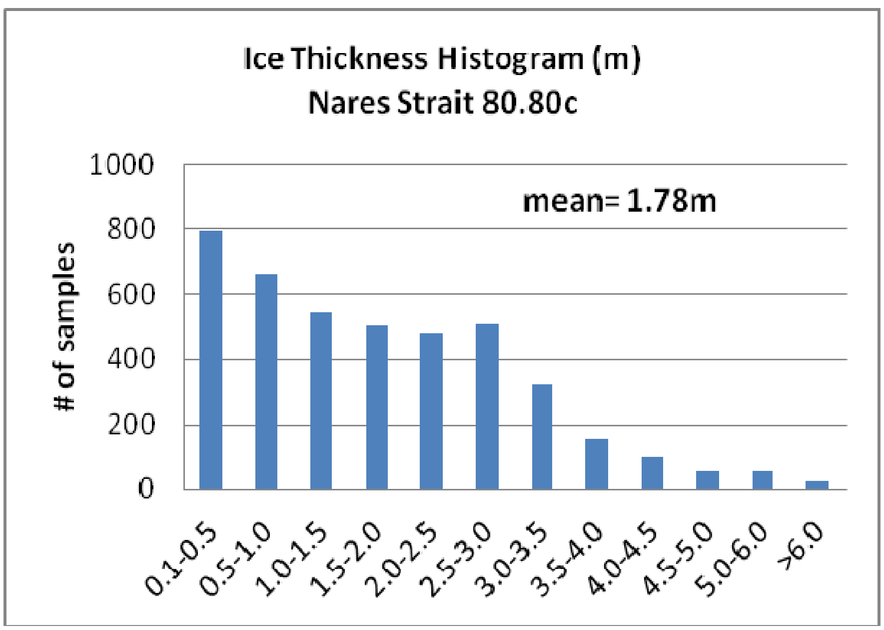


Fig. 31 Ice thickness histogram of transect 80.80 (modal 1.61m).

Nares Strait transect 81.05

Profile data for the transect 81.05 was collected flying West on August 21 and stored as file FEM1309. The file has 5520 data samples and one Background between 2321-2926 sample numbers or 605 samples where no ice data is collected. The flight path is not straight to sample ice rather than fly over open water. This track realignment at 40m altitude was between 4000-4115 for another 115 sample points where ice data was collected. Total number of data points to be discarded is 605+115 or 720 points.
This leaves 5520-720= 4800 data points for possible perfect ice data set. The actual number of ice samples collected with thicknesses >10cm was 3647; so ice concentration is 3647/4800= 76.0%. The sum of ice samples for ice thicker than 10cm was 6398.21; therefore the mean ice thickness is 6398.208/3647 or 1.75m.

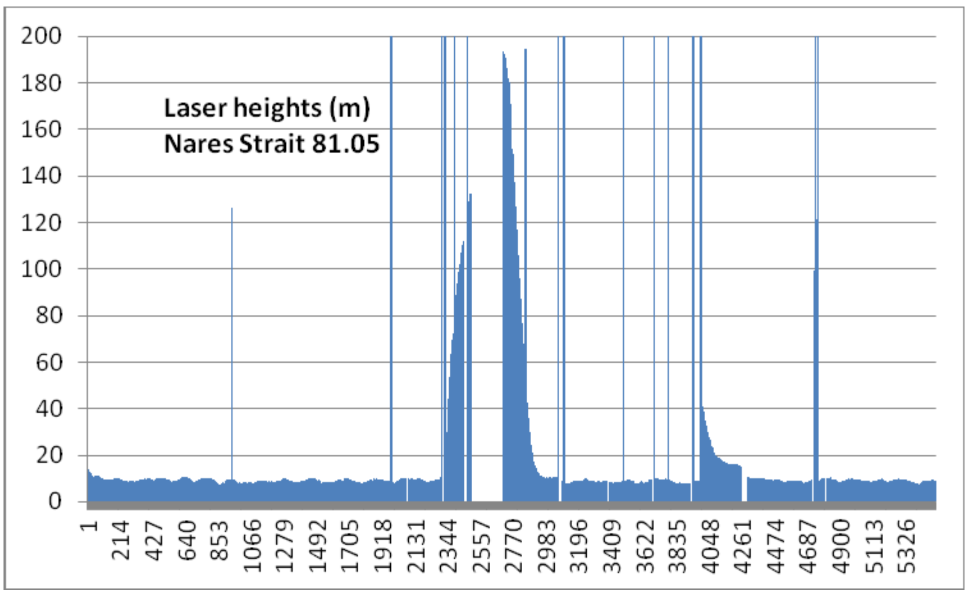


Fig. 32 Time series Laser height profile of Transect 81.05 showing laser spikes and one Background calibration peak.

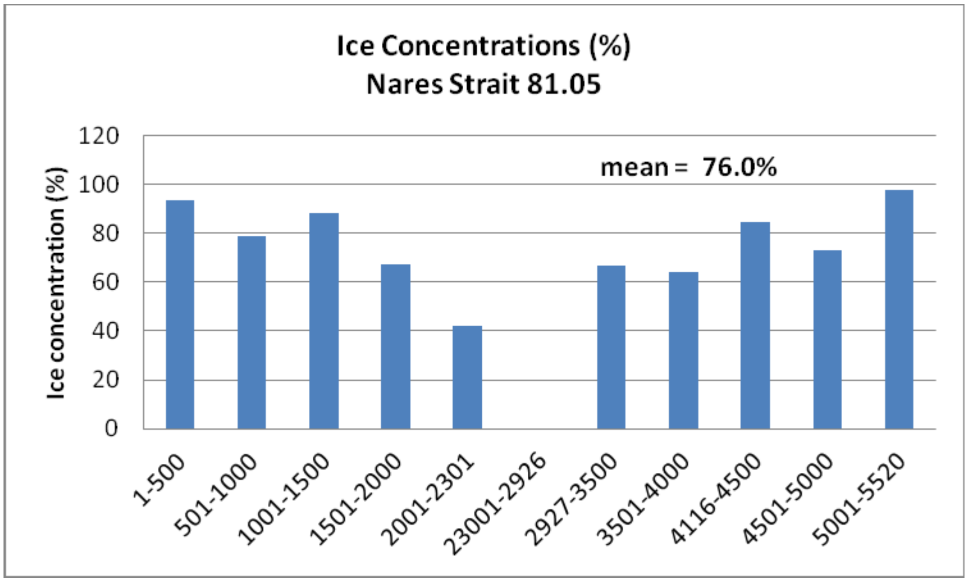


Fig. 33 Subsections' mean ice concentrations for transect 81.05.

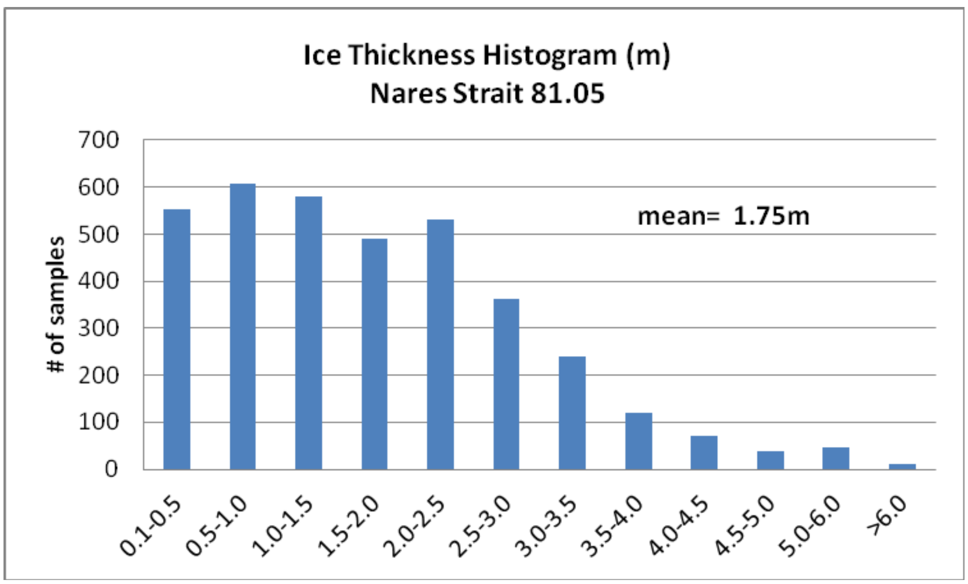


Fig. 34 Ice thickness histogram of transect 81.05 (modal 1.59m).

Nares Strait transect 81.10

The data for the transect 81.10 is stored as FEM13006 and was collected on August 21 flying East from 65.7^{o} to 64.95^{o} W. It has 5387 data laser points but also one Background peak between sample points 2590-3167 for a total of 577 points. Therefore 5387-577= 4810 sample points where ice data could have occurred. But since we have only 3896 ice data of thickness >10cm, the ice concentration 3896/4810= 81%. The sum of the ice data >10cm = 7571.018 and when divided that by 3896 points provides a mean ice thickness of 1.94m.
A large lead was avoided and flown over at 20m+ altitude at the start of the profile (580-755); but it should be counted towards (and decreasing) the ice concentration.

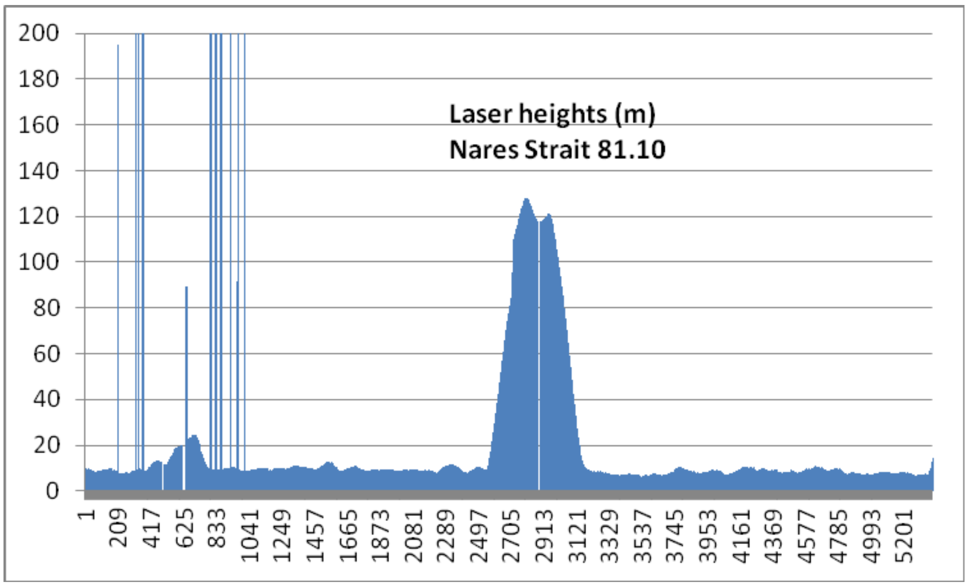


Fig. 35 Time series Laser height profile of Transect 81.10 showing laser spikes, one Background calibration peak and second peak where the helicopter increased its altitude while passing over a wide lead.

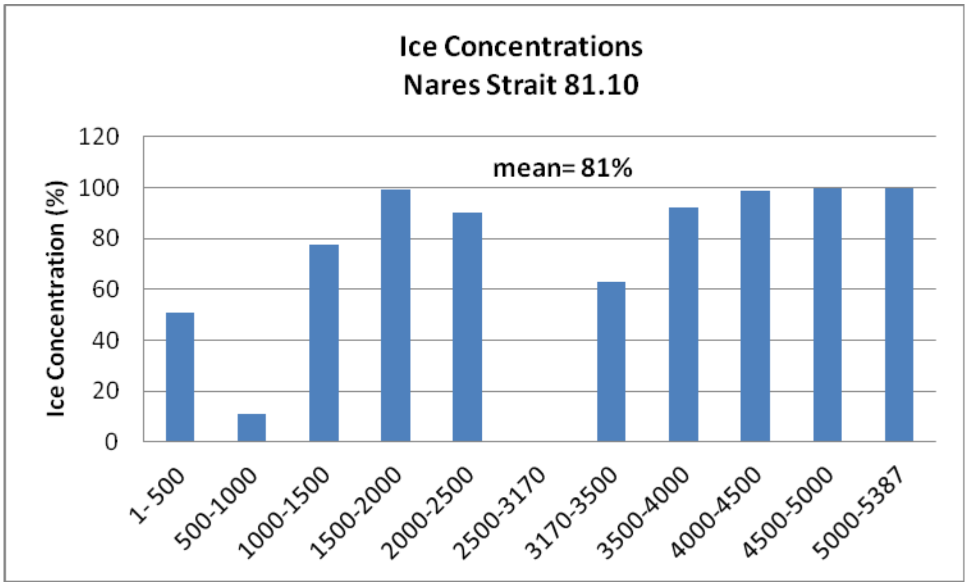


Fig. 36 Subsections' mean ice concentrations for transect 81.10.

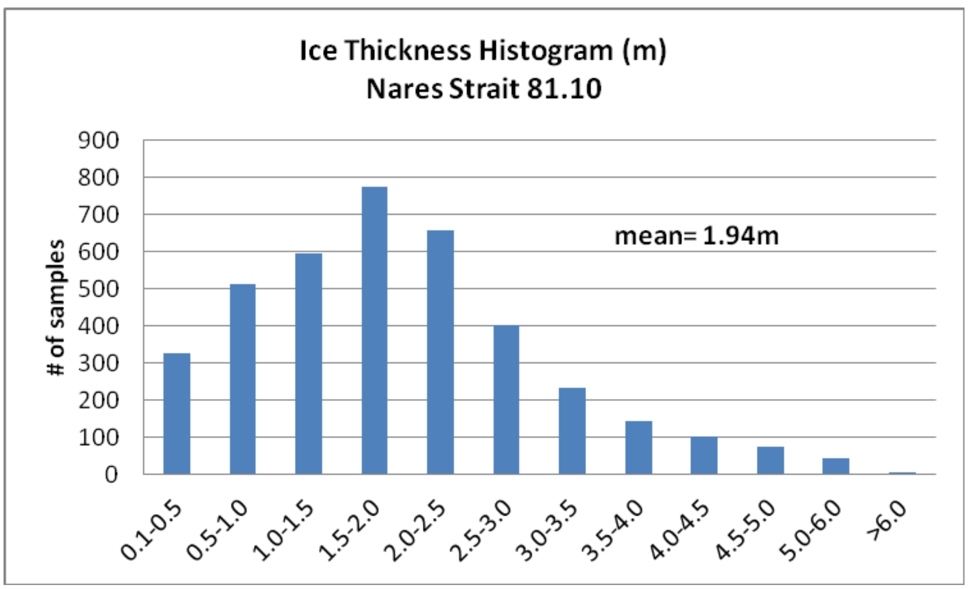


Fig. 37 Ice thickness histogram of transect 81.10 (modal 1.85m).

Summary of ice thickness transect data

Some of the results of the plots shown above of the five transects are listed in Table 2 along with the mean of all five transects and other derived parameters. The meaning and calculation for each row of the table are explained below the table.

Table 2. Ice features of five transects surveyed across Kennedy Channel in the summer of 2013 and their combined means.

1	Mid-transect's latitude (deg)	80.40	80.55	80.80	81.05	81.10	mean of 5 transects
2	EM/Laser data files	FEM 13016	FEM 13017	FEM 13011 FEM 13012	FEM 13009	FEM 13006	--------
3	Data collected	Aug. 24	Aug. 24	Aug. 23	Aug. 21	Aug. 21	--------
4	Sampling to	West	East	West	West	East	
5	Transect width (km)	37.0	36.5	35.0	29.0	29.5	33.0
6	Length (km/%) sampled	27.5/ 74.3	24.5/ 68.1	25.0/ 83.3	21.0/ 72.4	20.0/ 67.8	23.6/ 71.5
7	Length (km/%) not sampled	9.5/ 25.7	12.0/ 31.9	10.0/ 16.7	8.0/ 27.6	9.5/ 32.2	9.4/ 28.5
8	Possible ice data points	6226	5359	6014	4800	4810	27200
9	Actual ice data points	3666	2764	4195	3647	3896	18168
10	Pack ice (%) concentration along transect	58.8	51.8	69.8	76.0	81.0	66.8
11	Pack ice width (km) / and % of transect width	18.2/ 49.2	15.4/ 42.2	19.0/ 54.3	16.9/ 58.3	17.5/ 59.3	17.4/ 52.7
12	Mean ice (m) thickness with leads included	1.44	1.24	1.32	1.38	1.69	1.41
13	Ice-only mean/ modal thickness (m)	2.22/ 1.99	1.97/ 1.84	1.78/ 1.61	1.75/ 1.59	1.94/ 1.85	1.94/ 1.77
14	Ice cross-sect. area ($10^4 m^2$)	3.96	3.04	3.30	2.90	3.38	3.33
15	Thick floes >2.5m, mean thickness and frequency	3.74m 35.5%	3.54m 30.4%	3.40m 28.0%	3.39m 24.4%	3.38m 26.5%	3.50m 29.5%
16	Ice hazard frequency (>4m thick)	12.4%	7.2%	5.5%	4.6%	5.6%	7.1%

First row - is the mid-latitude of each transect and used as a file name for the specific transect in lists and diagrams.
Second row - is the EM data file number where the data can be found, and the 4th row shows if the data was collected flying East or West.
Third row - is the day the data was collected.
The 5th row - lists the **width of Kennedy Channel** at the transect's location.
The 6th row - lists the length of ice section surveyed along the transect. This is always less than the total width listed in row 5th as low flying ice surveying was stopped when large open water areas were encountered at the edge of the pack ice. Thus this length in the 6th row is an estimate of the **width of the pack ice** and % of the transect width the pack ice covers.
7th row - is the complement of 6th row and gives length of the open water area or very low concentration of pack ice at each transect that was not sampled.
8th row - lists the number of possible ice data points that could have been available along the survey line.
9th row - lists the actual ice data points collected for ice thicker than 10cm along the survey line.
10th row – uses the data from row 8th and 9th to derive the **ice concentration** of ice thicker than 10cm along the survey line. It includes the ice rubble fields where open water areas exist but can not be identified due to the EM large footprint. The frequency of this "thin" or no ice is listed in the histogram in the 0-10cm bin. It is an important number as one can subtract the "No ice" from the ice component to determine the ice-only thickness.
11th row - uses the length of water and thin ice (<10cm) along the surveyed line (row 7th) and calculate the length of the surveyed line where ice greater than 10cm was observed and thus is an estimate of the **width of the transect covered with a solid ice cover**.

12th row - provides the **mean ice thickness** of all the ice data collected along the transect section surveyed and includes the open water areas and leads.
13th row - provides the **mean/modal transect ice-only thickness** when the "thin and no ice" in the 0-10cm bin has been removed and is the best value to be used if one is asked: "What is the mean/modal ice thickness of the pack ice?". But due to the large EM foot print (of 20m over rubble pack ice) these ice thicknesses still includes a lot of open water area. (Note that the mean floe thickness was found to be 2.95m, this larger value does not include the brash ice between floes as the values of the 12th row above do).
14th row – lists the **cross-sectional ice area** of each transect and is the product of the mean ice thickness (12th row) and the surveyed length of the pack ice (6th row). It can be used as done later in the report along with the available ice beacon data to provide an ice flux through Kennedy Channel for the 2-3days in August when the ice thickness data were collected.

Rows 15th and 16th are of particular interest for ice engineering and transportation safety issues. The 15th row lists the frequency and mean ice thickness of ice observations thicker than 2.5m. And the last row lists the frequency of ice observations than 4m (ice hazards). It should be noted at those ice thickness of 4m, (plus 6m of helicopter altitude) the EM foot print is 30m {3x(ice plus altitude)} and thus each sample represents a large deep ice feature embedded within the floe.

In summary from the last column, the 5 transects across Kennedy Channel surveyed by the EM-Laser system had a mean width of 33.0km ranging from 29.0km to 36.5km. On average, pack ice was covered over 71.5% of the transect widths or over 23.6km. The remaining sections of the transects (28.5% or 9.4km as a mean for the 5 transects) was not surveyed for safety issues due to the very low ice concentrations. Along the surveyed line sections, a mean ice concentration of 66.8% was observed ranging from 51.8% in the south to 81.0% in the north. After removing the open water and thin (<10cm) ice areas within the pack ice, the ice covered (as a mean of all five lines) 17.4 km or 53% of the width of the total Channel.

The mean ice thickness along the survey lines was 1.41m when leads and open water areas within the pack ice was included. When the leads and open water within the surveyed sections are excluded, the pack ice had a mean ice-only thickness of 1.94m (modal 1.77m). Even this thickness includes a lot of open water area where small ice floes and brash ice occurs because of the large EM foot print.

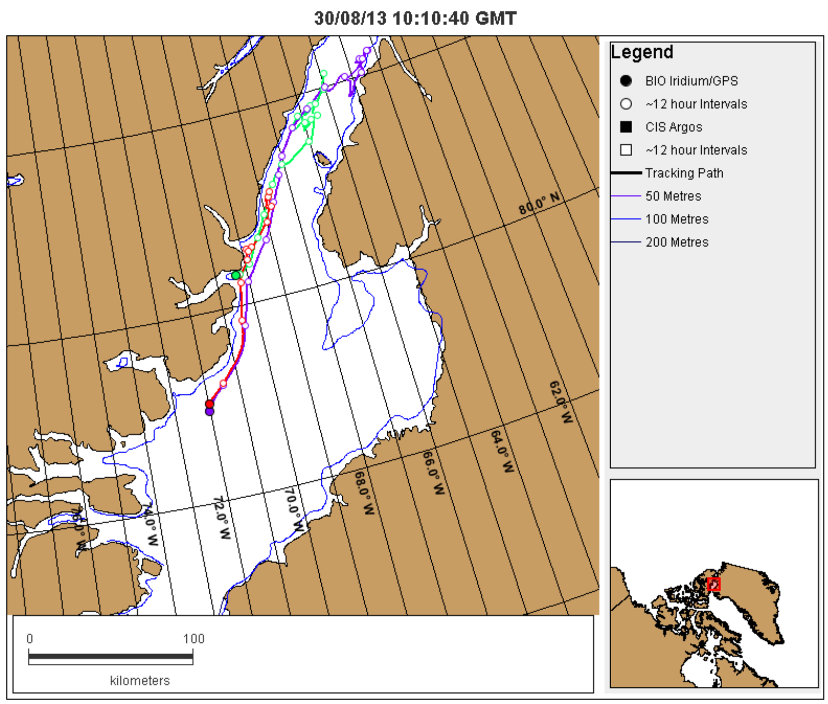
The large thick ice (> 2.5m) occurred on average for the 5 transects 29.5% and ranged in occurrence from 24.4% to 35.5% for the transects (row 15 table 2). The mean thickness of ice thicker than 2.5m was 3.50m. When looking at ice hazards within the pack ice, ice thicker than 4m occurred on an average 7.1%.

Satellite-tracked ice beacons

Fig. 38 Iridium beacon deployed on a MYI floe in Kennedy Channel (above) and beacons with 2” ice auger used to deploy the beacons (below).

As part of the Amundsen ice survey, three ice beacons were deployed on pack ice to calculate the ice volume flux through Nares Strait, and 15 ice beacons were deployed by CEOS personnel on tabular icebergs (ice hazards) in Northern Baffin Bay to study the drift response of these ice hazards to wind and ocean current forcing. Some large tabular icebergs were actually grounded. The data would also provide information on the difference of ice drift of pack ice versus ice hazards that extended deeper into the water column; a study is underway at CEOS of the University of Manitoba. Here we briefly discuss the beacon data as needed to obtain the ice volume flux in Kennedy Channel.

Fig. 39 shows an example of the ice beacon tracks of three beacons deployed on sea ice and available from the Bedford Institute website under data products/ice beacon drifter: http://www.bio.gc.ca/science/research-recherche/ocean/ice-glace/index-eng.php . The circles show the 12hr locations of the beacons of the hourly location time series. All three beacons travelled during August 26 through 28 along the Canadian coast of the southern part of Kennedy Channel at about 15-25km/day or 15-25cm/s with beacon 3857780 (purple track) being farther offshore traveling the fastest due to less coastal frictional affects. Kwok (2005) using satellite data found a similar mean ice drift of 20km/day at the northern entrance to Nares Strait for the mobile ice seasons of 1996 to 2002 while investigating the ice flux entering Nares Strait from the Lincoln Sea. The 2013 beacon data showed that the drift rate south is very variable and at times the ice beacons moved northwards for a short time periods. Beacon 3857780 was deployed on the Greenland side of the Kennedy Channel on August 21 and crossed the Channel after 2.5 days to move quickly southwards. Beacons 3857810 and 3857780 (red and purple tracks) traveled together on Aug. 29 about 30km southwards in 12hrs or 65cm/s; as ice drifts at 2.5-3.0% of the wind speed (Mcphee, 1980), half the drift rate is due to the wind drag on the ice and half by the drag of the southward directed surface layer water currents which also responded to the strong N to NW winds of 25knts. *There is "enough anecdotal evidence to know that the surface flow is much more energetic than that at the shallowest water column level (35-40 m) and relatively weakly coupled to it" (H. Melling, 2014 personal communications).*



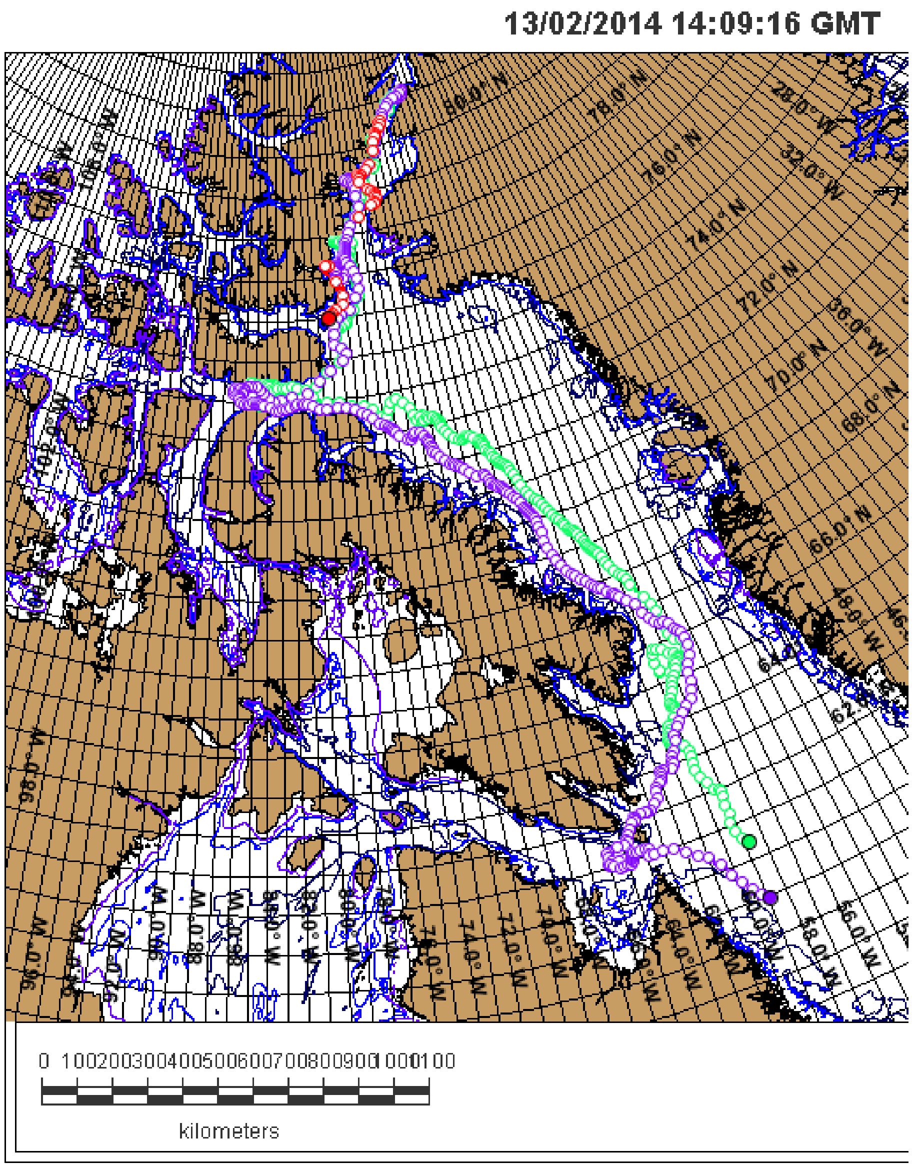
Most Recent Data									
SYMBOL	BID	GPS_DATE	LATITUDE	LONGITUDE	FIRM_WARE	TEMP_1	TEMP_2	TEMP_3	AIR_TEMP
	3853820	2013-08-30 07:00:00.0	80.1620	-70.3520	1.4.1	-31.7000	-32.3000	-33.7000	-32.7000
	3857780	2013-08-30 07:00:00.0	79.4905	-72.0159	1.4.1	-31.6000	-32.3000	-33.6000	-32.8000
	3857810	2013-08-30 07:00:00.0	79.5245	-71.9716	1.4.1	-31.4000	-32.1000	-33.5000	-32.7000

Fig. 39 Ice beacon tracks of three beacons deployed on sea ice in August 2013.

With a mean ice drift of 20cm/s, the ice flux leaving Kennedy Channel during August 26-28 was 0.2m/s x $3.33 \times 10^4 m^2$ or $6.66 \times 10^3 m^3/s$ ($5.8 \times 10^{-2} km^3$/day or 6.7mSv) since the mean ice cross-sectional ice area was $3.33 \times 10^4 m^2$ (Table 2) where a mSv is an oceanic water transport unit of $10^3 m^3/s$. This ice transport is small in comparison to the water volume transport through Kennedy Channel which is two orders of magnitude larger (0.57Sv, Munchow and Melling, 2008), and small compared to the freshwater transport through Kennedy Channel (28mSv extrapolated to surface, Rabe et al., 2012). Even when the drift rate increases to 65cm/s, the ice flux (0.02Sv) remains small in comparison to the water and freshwater fluxes as these too will increase over the short periods when Northerly winds occur.

In comparison, the annual mean ice flux entering Nares Strait during the years 1996 to 2002 was 4.0mSv (Kwok, 2005), spreading the flux over the mobile ice season of 184days (Kwok et al., 2010), the ice flux increases to 8.0mSv ($6.9 \times 10^{-2} km^3$/day) similar but larger than found (6.7mSv or $5.8 \times 10^{-2} km^3$/day) in this study for August 2013 leaving Nares Strait. Kwok et al. (2010) extended the time series of the ice flux entering Nares Strait to 1997-2009 using ice drift and estimates of multiyear sea ice coverage from high resolution SAR imagery acquired by RADARSAT and Envisat, and ice thickness is from ICESat. They estimated an average annual (September-August) ice volume flux of $141 km^3$, larger than the flux of $130 km^3$ from a shorter 6□year record between 1996 and 2002 [Kwok, 2005]. The larger (~10%) average in the longer record are due to two consecutive years (2007 and 2008) of high outflows (Kwok et al., 2010).

The yearly mean ice flux entering Nares Strait (Kwok et al., 2010) ranged from a low of $10 km^3$ over 123days or $8.1 \times 10^{-2} km^3$/day for the 04-05 mobile ice season to $250 km^3$ over 350 days or $71.3 \times 10^{-2} km^3$/day for the 06-07 mobile ice season. The ice flux for August 2013 ($5.8 \times 10^{-2} km^3$/day) leaving Nares Strait is less than the flux range values entering Nares Strait found by Kwok et al., 2010). The difference can be attributed in part to the pack ice evolution in the summer months as the pack ice decays while moving south through Kennedy Channel in addition to the large monthly and seasonal variabilities as seen by Kwok (2005) and Kwok et al., 2010). In this study the ice leaving Nares Strait for the summer of 2013 was only 1.94m thick and covered just 53% of the Channel's width; it consisted of decaying MY ice, local grown FY ice and thin brash ice. As stated by Kwok (2005) "*South of the gate (entrance to Nares Strait), the MY ice coverage is highly variable and the strait may be filled with multiyear or seasonal ice*". The summer pack ice composition thus changes along the length of Nares Strait and both solid and liquid ice contributions need to be considered in budget calculations.



SYMBOL	BID	GPS_DATE	LATITUDE	LONGITUDE	FIRM_WARE
Most Recent Data					
green	3853820	2014-02-12 22:00:00.0	60.4426	-59.7901	1.4.1
purple	3857780	2014-02-13 10:00:00.0	58.9301	-59.9016	1.4.1
red	3857810	2013-09-22 21:00:00.0	76.0291	-78.8097	1.4.1

Fig. 40 Trajectories of beacons deployed in Nares Strait in August 2013 and reporting their positions until mid February 2014 along the northern Labrador Shelf.

Beacons 3853820 and 3857780 (green and purple tracks) travelled together down the Baffin Island coast and into northern Labrador shelf area where they stopped reporting by mid–February 2014, six months after they were deployed (Fig. 40).

Conclusions

During the ArcticNet 2013 summer survey in the Canadian Arctic, a unique ice property data set was collected with helicopter-borne sensors from the pack ice in northern Nares Strait (Kennedy Channel). The data was collected during the transits of the CCGS Amundsen to and from the Petermann Glacier whose fjord was entered on August 22 and explored to the Glacier's front.

The pack ice in Kennedy Channel, surveyed on August 21, 23 and 24, consisted of old First-Year Ice (FYI) and thick Multi-Year Ice (MYI) either as individual floes or as large composite FY-MY ice floes. The mean total width of the five transects across the Channel was 33.0km which a range of 29.0km to 36.5km. On the average, pack ice with high ice concentrations was found over 71.5% of the Channel width or 23.6km. The remaining section of the Channel had as a mean a very low ice concentration that was not surveyed for safety issues (28.5% or 9.4km). The mean ice concentration along the five transects was 66.8% and ranged from 51.8% in the south to 81.0% in the north. The ice covered 53% of the Channel mean width when open water and thin ice (<10cm) areas between the floes were eliminated.

Ice floes greater than 100m in length had a mean ice thickness of 2.95m. Of these 140 identified floes, half were composite FY-MY, 1/3 MYI and 1/6 FY ice floes. When the ice rubble was included in the mean thickness calculations for the five transects across Kennedy Channel, the thickness of the pack ice reduced to a mean of 1.94m (modal 1.78m), ranging from 1.75m to 2.2m (modal 1.59m and modal 1.99m respectively). As stated in Flato and Brown (1996) "*even as far north as Alert near the northern tip of Ellesmere island, at approximately 82.5^{o}North, the un-deformed landfast ice in protected in bays is seasonal, reaching a maximum of 2.0 – 2.5m in winter and melting completely almost every summer.*"

The FY ice floe thicknesses observed in this survey had a similar range with a mean of 2.41m (modal 2.3m). The MYI floes observed in the late summer had a mean of 3.62m (modal 3.51m), thinner than the late winter maximum thickness observed in 2004 and 2005 by Haas et al. (2006) in the Lincoln Sea just north of Nares Strait. Their observations in May 2004 had a mean of 4.67m (modal 3.9m) and in May 2005 a mean of 5.18m (modal 4.2m). These thicknesses were used by Kwok (2005) to calculate ice fluxes; they are winter maximum thicknesses that would decrease due to melting in the summer months as the pack ice moved south through Nares Strait.

Ice cross-sectional areas across Kennedy Channel were computed for five transects, they ranged from 2.90 to 3.96 $x10^4m^2$ with a mean of $3.33x10^4m^2$. At a general drift rate of 20cm/s, the snapshot ice flux leaving Kennedy Channel during August 26-28 would have been 0.2m/s x $3.33x10^4m^2$ or $3.66x10^3m^3/s$ ($5.8x10^{-2}km^3$/day or 6.7mSv). Kwok (2005) showed that the mean ice flux entering Nares Strait from the Lincoln Sea over ½ year-long mobile ice season was $6.9x10^{-2}km^3$/day, consisting mostly of 4m thick MYI. Monthly mean volume ice flux values ranged greatly from $8.13x10^{-2}km^3$/day to $71.3x10^{-2}km^3$/day (Kwok et al., 2010). Aside from monthly and seasonal variability, the differences in summer ice flux entering and leaving Kennedy Channel shows that the pack ice melts as in transects through Kennedy Channel and this pack ice evolution should be consider in freshwater fluxes. Not only are the surface ice and oceanic fluxes hard to measure due to possible mooring damage by ice (Munchow and Melling, 2008), it is also important where along the Channel the measurements are done in order to obtain all the components of the ice and ocean freshwater budget that enter and leave Nares Strait. Analysis of the available mooring and satellite data is continuing in order *to get reasonably continuous and reliable time series of surface velocity ice drift* (H. Melling, 2014 personal communication) to understand the freshwater budget components of Nares Strait.

The late summer ice transport of 6.7mSv out of Kennedy Channel obtained in this study, even if continuously throughout the summer, is small in comparison to the water transport (0.57Sv, Munchow and Melling, 2008) which is two orders of magnitude larger and even compared to the oceanic freshwater transport through Kennedy Channel (28mSv, Rabe et al., 2012) which is still one order of magnitude larger. Even if the ice drift rate increases under northerly winds so will the oceanic fluxes and thus the ice flux will remain small in comparison to these oceanic fluxes.

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