Labrador Shelf Pack Ice and Iceberg Survey, March 2011

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Labrador Shelf Pack Ice and Iceberg Survey, March 2011

by

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Table of Contents . . . . **Page**

List of Figures

List of Tables

.

Abstract

Prinsenberg, S.J., I.K. Peterson, J.S. Holladay and L. Lalumiere, 2012. Labrador Shelf Pack Ice and Iceberg Survey, March 2011. Can. Tech. Rep. Hydrogr. Ocean Sci. 275: vii+44pp.

This report presents examples of data collected in March 2011 off the mid-Labrador coast using helicopters from Canadian Helicopters Ltd. in Goose Bay, Labrador. The week-long survey collected ice thickness and ice roughness data with helicopter-borne Electromagnetic-laser (EM) sensors and snow thickness data with a Ground-Penetrating-Radar (GPR) sensor flown both at 5-7m altitude along seaward flight paths, and video and roughness data with a video-laser system flown at 100m altitude along shoreward flight paths. A total of 430 kilometres of ice thickness and snow thickness profile data along low-flying survey lines and 430 kilometres of video data were collected along high-flying survey lines. Eight satellite-tracked ice beacons were deployed as pairs on icebergs and neighbouring ice floes to monitor their relative southward drift rates in response to wind and ocean forcing. In comparison to observations from the 2009 survey which was done on the same date in the same area, the 2011 pack ice was much reduced in extent and in thickness.

The snow and ice cover on Lake Melville was sampled with the EM and GPR systems. Lake Melville is part of a large estuary, with a freshwater surface layer due to outflow from the Churchill River and other rivers, and a saline lower layer. The EM data indicated that the freshwater surface layer was up to 5m thick and the GPR could sample the low salinity ice thickness of the western part of the lake. A hand-lowered CTD verified the existence of the surface freshwater layer. The GPR-laser system measured snow thicknesses up to 40cm on Lake Melville but also large regions of bare ice were encountered. All data, plots, photographs and reports are available through the Dept. Fisheries and Oceans Maritimes Region's "SeaIce" Website: http://www.mar.dfo-mpo.gc.ca/science/ocean/seaice/public.html and its FTP data link: ftp://starfish.mar.dfo-mpo.gc.ca/pub/ocean/seaice/.

Résumé

Prinsenberg, S.J., I.K. Peterson, J.S. Holladay and L. Lalumiere, 2012. Labrador Shelf Pack Ice and Iceberg Survey, March 2011. Can. Tech. Rep. Hydrogr. Ocean Sci. 275: vii+44pp.

Le présent rapport offre des exemples de données recueillies en mars 2011 au large du milieu de la côte du Labrador à l'aide d'hélicoptères de Hélicoptères Canadiens Limitée, à Goose Bay, au Labrador. Le relevé, effectué sur une semaine, a recueilli des données sur l'épaisseur et la rugosité de la glace grâce à des capteurs électromagnétiques laser héliportés et des données sur l'épaisseur de la neige grâce à un géoradar, qui volaient à une altitude de 5 à 7 m le long des trajectoires de vol vers la mer, ainsi que des données vidéo et des données sur la rugosité à l'aide d'un système vidéo laser, qui volait à une altitude de 100 m le long des trajectoires de vol vers le rivage. Au total, des données sur le profil d'épaisseur et de rugosité de la glace ont été recueillies sur 430 kilomètres le long des lignes de levé à basse altitude, et des données vidéo ont été recueillies sur 430 kilomètres le long de lignes de levé à haute altitude. Huit balises de glace suivies par satellite ont été déployées en paire sur des icebergs et des floes avoisinants afin d'observer leurs vitesses de dérive relatives vers le sud sous l'effet du forçage éolien et du forçage océanographique. Comparativement aux observations du relevé de 2009, qui a été mené à la même date dans la même région, l'étendue et l'épaisseur des banquises de 2011 étaient grandement réduites.

La couverture de neige et de glace sur le lac Melville a été analysée grâce au système électromagnétique laser et au géoradar. Le lac Melville, qui fait partie d'un grand estuaire, se caractérise par une couche d'eau douce en surface attribuable au déversement de la rivière Churchill et d'autres rivières, ainsi que par une couche inférieure d'eau salée. Les données recueillies par le système électromagnétique laser indiquent que la couche d'eau douce en surface avait une épaisseur allant jusqu'à 5 m, et le géoradar pouvait analyser la faible épaisseur de la glace saline de la partie ouest du lac. Une sonde CTD descendue à la main a confirmé l'existence de la couche d'eau douce en surface. Le système électromagnétique laser et le géoradar ont mesuré des couches de neige allant jusqu'à 40 cm d'épaisseur sur le lac Melville, mais ont aussi rencontré de grandes régions de glace nue. Les données, les graphiques, les photographies et les rapports se trouvent sur le site Web de l'étude des glaces de mer de la région des Maritimes de Pêches et Océans Canada à l'adresse http://www.mar.dfo-mpo.gc.ca/science/ocean/seaice/public.html et sur le lien de données FTP ftp://starfish.mar.dfo-mpo.gc.ca/pub/ocean/seaice/.

Introduction

In March 2011, an 8-day field program was conducted along the Labrador coast to collect snow and ice property data of the offshore pack ice and, in collaboration with the Canadian Ice Service (CIS), to deploy satellite-tracked ice beacons on icebergs and nearby ice floes. A similar survey was done during March 2009 (Prinsenberg et al., 2011) which provided a good comparison data set, as the 2011 winter was much milder than the 2009 winter. The observations of both surveys are actively being used by CIS and Dept. Fisheries and Oceans (DFO) personnel to validate sea ice signatures in RADARSAT-2 imagery and to collect ice thickness distributions for input to offshore regulation codes and engineering structure designs. The observations also contribute to the research by the Canadian Ice Service to identify icebergs within the pack ice in RADARSAT-2 imagery, and to understand the iceberg drift relative to the drift of ice floes.

Three separate helicopter-borne observation systems have been developed by Canadian companies for the ice observation program. They are mounted in a cigar-shaped sensor package attached beneath and in front of a Bell 206L helicopter (Fig. 1). The helicopter-borne electromagnetic (HEM) system (called "Ice Pic") measures ice-plus-snow thickness and ice-surface roughness. The Ground Penetrating Radar (GPR) sensor measures the snow-depths over the sea ice cover, as well as the thickness of low-salinity ice (Lalumiere and Prinsenberg, 2009). The Video-Laser sensor collects video images from which mosaics are made from overlapping video frames. For the Labrador Sea ice survey, the helicopter-borne systems were mounted on a Bell 206L helicopter from Canadian Helicopters Ltd. (CHL) stationed in Goose Bay. A second Bell 206L helicopter on fixed floats flew along with the surveying helicopter for safety concerns and carried the extra survey gear. Iridium GPS and ARGOS ice beacons were deployed on icebergs and nearby ice floes to track sea ice and icebergs.

Ice and snow properties were also collected at Lake Melville while en route to and from Makkovik on the Labrador coast. At on-ice stations, snow thicknesses were measured and CTD profiles were collected to validate the GPR snow and the EM freshwater plume thicknesses at the western end of the Lake. The survey completed most of its planned tasks as described briefly in this technical report. All data, pictures, notes and reports will be available on the DFO's Maritimes Website: http://www.mar.dfo-mpo.gc.ca/science/ocean/seaice/public.html and through its data link on the DFO's Maritimes FTP site: ftp://starfish.mar.dfo-mpo.gc.ca/pub/ocean/seaice/.

Instrumentation

Electromagnetic-Laser Sensor

During the 8-day 2011 field survey, ice thickness and ice surface roughness were measured with a helicopter-borne electromagnetic (HEM) system, called the "Ice Pic" and built by Geosensors Inc. of Toronto, Canada. The sensor package consists of an electromagnetic (EM) sensor with transmitter, receiving coils (transmitter frequencies of 1.7, 5.0, 11.7 and 35.1 kHz) and a laser altimeter. The laser altimeter data provides ice-surface roughness profiles and the height of the EM sensor above the pack ice. The system used an ADM 3-Alpha Geophysical laser unit with listed accuracy of 1.5cm. The EM sensor measures the distance to the ocean surface water as it is the nearest conductor, and the laser measures the distance to the ice or snow surface. Together they provide the snow-plus-ice thickness. The sampling rate for the ice thickness and ice roughness data is 10Hz, which, given typical helicopter survey speed of 80mph, corresponds to a spatial sampling interval of about 3-4m.

The ice thickness and ice conductivity are estimated with a 2-layer inversion model representing ice and seawater layers. The calculations are done in real-time by a computer strapped in the back seat of the helicopter and the results displayed approximately 1sec later on a hand-held monitor used by the operator. The data are also post-processed after the survey to remove small EM drift effects.

Fig. 1 Canadian Helicopters Ltd. 206L helicopter with the fix-mounted sensor equipment (March 2011). The EM sensor is located in the outer section and the GPR and Video-Laser are located in the middle section of the “cigar” shaped mount.

The distance to the ocean surface water measured by the EM sensor used to infer the ice thickness is an average distance over the footprint of the EM sensor. The footprint size of the EM sensor depends on the height of the EM sensor above the seawater (Kovacs et al., 1995), and is 16-20m for the “Ice Pic” flying at 4m over 2m thick ice. The inferred ice thickness is thus an average over a 20-25m area and represents more an ice volume over 25m even though the sampling interval is 3-4m. Several studies have validated the EM ice thicknesses collected by both the “Ice Pic” and “Ice Probe”, a towed HEM system, by comparing EM ice thicknesses successfully with ice and snow thicknesses measured via holes drilled through the ice (Peterson et al., 2003 and

Prinsenberg et al., 2008). For flat homogeneous ice over sea water such as refrozen leads, no significant difference can seen between auger observations and EM helicopter data, as the differences are usually smaller than the variability in each data set. Over rough deformed ice, larger differences are expected and nearly impossible to validate.

Ground Penetrating Radar Sensor

Ground Penetrating Radars (GPRs) have the capability of measuring snow thickness or freshwater ice thickness (Lalumiere and Prinsenberg, 2009). A one-dimensional processing algorithm provides snow thickness, and if the underlying ice has low salinity (1-2psu), it also provides the ice thickness. For the 2011 survey, the GPR profiles could be viewed in real-time inside the helicopter which helped ensured that the data were being logged properly, whereas during the 2009 survey the data could only be viewed in a post-processing mode.

The GPR system is a Noggin-NIC 1000 from Sensors and Software Inc. of Mississauga, Ontario. A photograph of a Noggin-NIC 1000 is shown in Fig. 2. The system is 30cm long by 15cm wide and 12cm high and was mounted in the middle section of the 206L helicopter mount, with its bottom plate protruding outside the tube exterior. The Noggin-NIC 1000 is a unique GPR system which permits operation and control by a computer with no user interaction. This permits the integration of this GPR as an additional sensor into the Video-laser System. The Noggin-NIC 1000 is a very high resolution GPR system, with a center frequency of 1000 MHz and a waveform sampling interval of 0.1 nanoseconds. For this experiment, the device was configured to collect 500 points per scan with 4 internal stacks, which results in a scan rate of approximately 30 scans per second. When flying at 60-80 knots, the ground sample spacing is approximately one sample per 1.0-1.5m. This fine spacing permits the GPR to collect snow features at the same fine scale as the laser for surface ice roughness.

Fig. 2 Sensors and Software Noggin 1000-NIC GPR System (left) protruding from middle section of the mounting tube along with laser/video camera (right).

Video-Laser System

The Video-Laser system consists of the laser and video camera (Fig. 2). The 3-Alpha laser altimeter, manufactures by Optech Inc., measures the flying height and ice roughness; for a sampling rate of 30 Hz it provides a 1.5m sample spacing at a flying speed of 80mph. The digital camera used is an Axis 210 by Axis Communications. Images are typically collected at a rate of 2 Hz but the rate is determined by the logging system based on the image field of view, flying height and speed. Each image is 640 by 480 pixels in size, and with a typical flying altitude of 90-100m, each pixel covers approximately an area of 30cm by 30cm in size. The width of the video frame image equals 1.1 times the height of the video camera above the ice surface. Since the helicopter flies low (altitude 4 to 6m) when logging GPR and EM data; digital video images are not recorded during these survey lines. Video data were collected on the onshore flight paths, while EM and GPR data were collected on the out-bound flight paths. The Video-laser system also collects laser altimeter data for additional surface roughness determination.

GPS Sensors

Both the “Ice Pic” and Video-GPR systems have their own GPS sensors so that the systems can be flown independent of each other if either were to malfunctioned. The GPS units used are Garmin GPS18’s made by Garmin International Inc., Olathe, USA. The GPSs include an embedded receiver and an antenna, and track up to 12 satellites at a time, while providing fast time-to-first-fix and precise navigation updates once per second. The units are designed to withstand rugged operations, are waterproof and require minimal additional components to be supplied by a system integrator. The “Ice Pic” and Video-GPR systems provide the GPSs with power. A Clear view of the GPS satellites is required for optimal performance. Listed position accuracy are given as <15m, 95% of the time.

Survey Description

Survey lines

A sensors’ test flight was successfully flown on Wednesday morning after spending the whole previous day mounting the systems. Weather was not favourable to do the survey off the coast until later in the week, so GPR work planned for one or two days near Goose Bay was done. Snow thicknesses and freshwater plume layer depths were collected from only the western end of Lake Melville on Wednesday and Thursday as weather prevented us from surveying farther east over the Lake (Fig. 3).

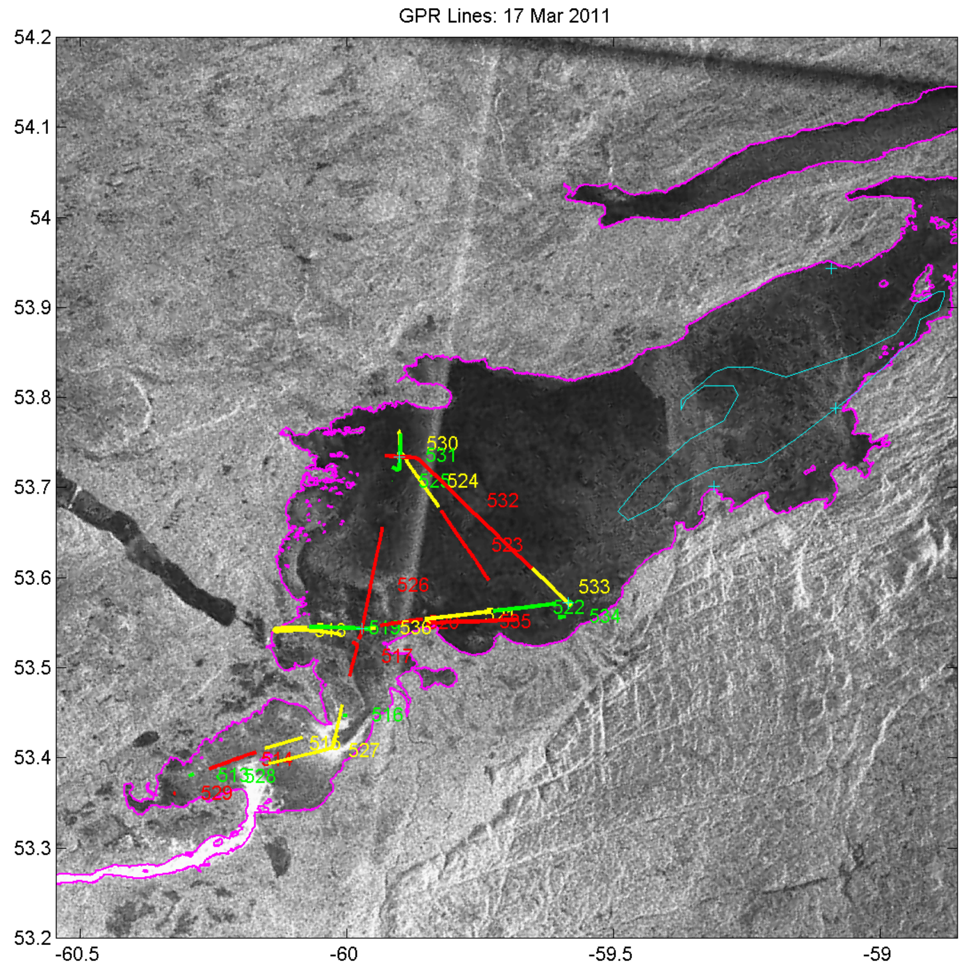

Fig. 3 Flight paths flown on March 17 were restricted due to weather to the western section of Lake Melville and shown overlain on a 100kmx100km RADARSAT-1 image of March 21. Colour line sections along with numbers indicate the GPR data profiles collected on March 17, (© RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2011) - All Rights Reserved).

The weather finally cleared late Friday and both helicopters left early Saturday (March 19) for Makkovik via Lake Melville and crossing the coastal mountains near Rigolet. Nolan Walsh was flying the survey helicopter, with Scott Holladay and Simon Prinsenberg running the data collection systems over Lake Melville. Chris Rodway would switch over as survey pilot by the afternoon after finishing a tricky drill replacement job along the Labrador coast. Dean Burry flew the second helicopter and was accompanied by helicopter engineer Andrew Parsons and Ingrid Peterson, his helicopter carried all personal gear, beacons and on-ice instrumentation. Snow and freshwater plume data were collected along the flight path over Lake Melville.

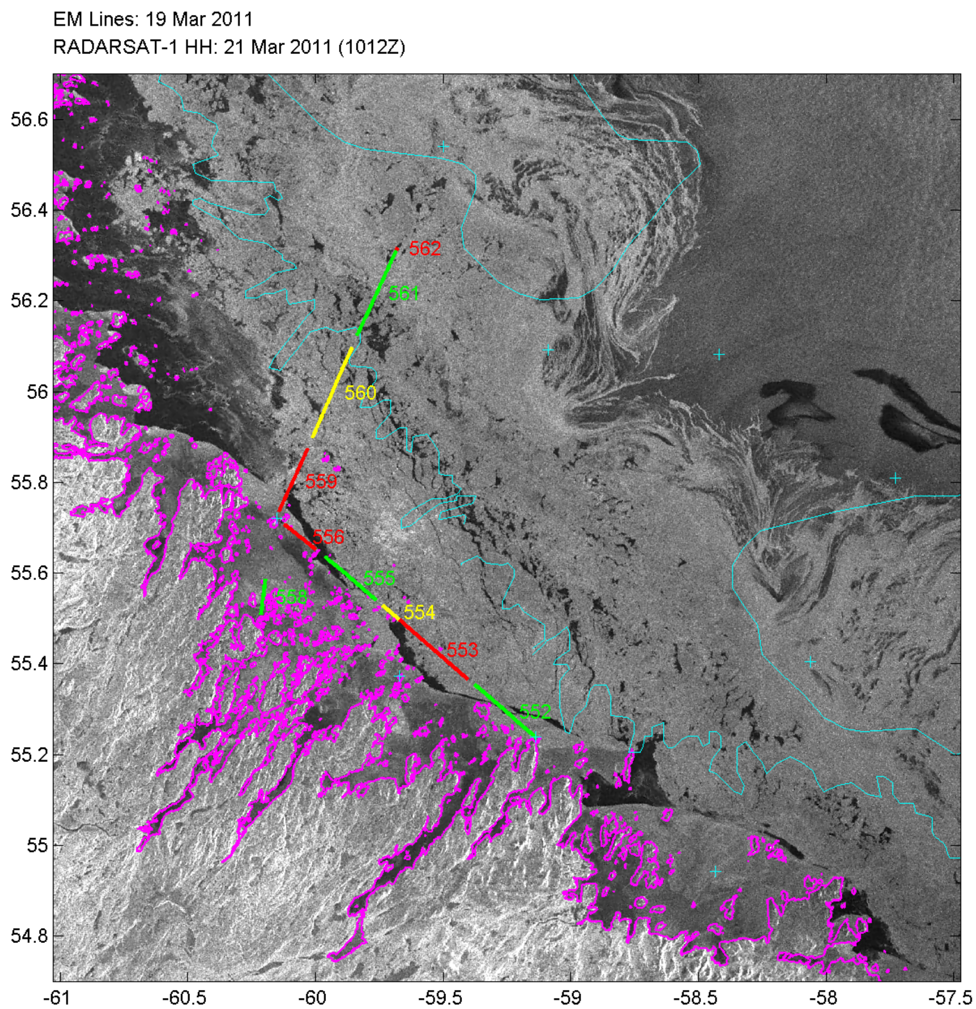

Fig. 4 Flight paths flown on March 19 overlain on a 200kmx200km RADARSAT-1 image of March 21. Line between Makkovik and Hopedale, parallel to coast is ~90km long and offshore EM-GPR flight line is the ~70km long, coloured section and numbers refer to GPR file data sections. (© RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2011) - All Rights Reserved).

After dropping off the gear at the hotel and refuelling at the Makkovik airport (13:30), the helicopters were ready to survey (Chris Ordway in the survey helicopter and Dean Burry and Andrew Parsons in the second helicopter). An EM-GPR survey line was flown along the land-fast ice to Hopedale, where we refuelled (15:15) before doing a offshore EM-GPR flight line along the "Hopedale Line" looking for icebergs to deploy beacons on (Fig. 4). Stopped the offshore survey line short at 16:04 and turned to the tabular iceberg north of the line on which the crew of the second helicopter placed an ARGOS beacon 12997 and an ARGOS beacon 16797 on the nearby pack ice. Video data were collected along the Hopedale Line shoreward line; early along the line a second set of beacons (beacons 12995 and 11254) were deployed on a pinnacle iceberg and nearby ice floe. From the pinnacle iceberg, video data were collected along the “Hopedale Line” (17:18), then along the same land-fast EM-GPR flight track back to Makkovik (17:40).

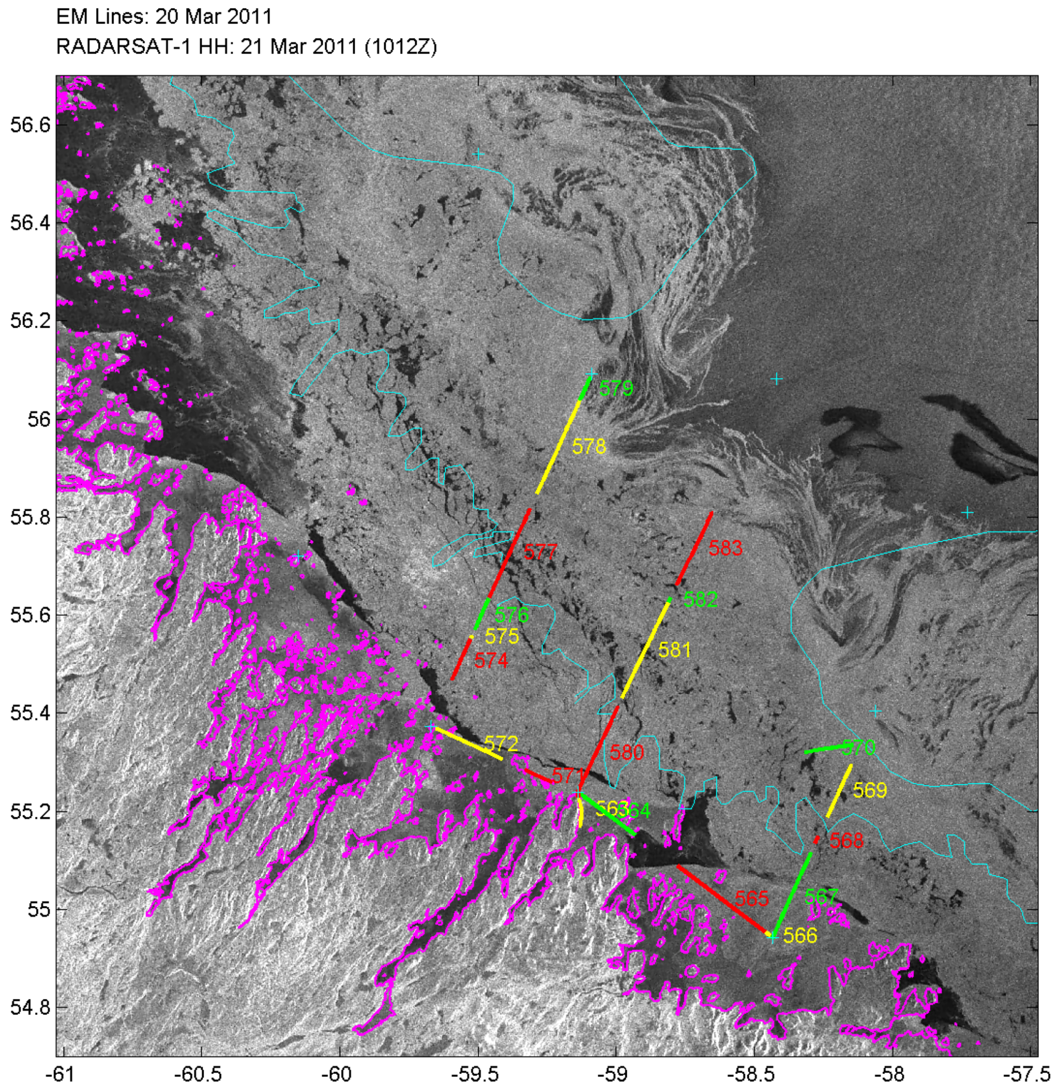

Fig. 5 Flight paths flown on March 20 overlain on a 200kmx200km RADARSAT-1 image of March 21. The offshore lines, going from SE to NW, are the “Mooring line” (~40km), “Makkovik line” and “Middle line” (~70km) (© RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2011) - All Rights Reserved).

On Sunday March 20, three offshore lines were flown (Fig. 5), and another two pair of beacons were deployed on ice floes and tabular icebergs by Ingrid Peterson using the second helicopter. The “mooring” line, (right offshore line in Fig. 5), just reached the offshore ice-ocean mooring location before the pack ice concentration became low and the ice moved extensively due to long period swells. The line completed half the planned line as indicated by the light blue crosses (planned end positions). At the end of the mooring line, a set of beacons were deployed on a small tabular iceberg and on a nearby ice floe. Next the “Middle” line (left offshore line in Fig. 5) was surveyed again, collecting EM and GPR data in the offshore direction, and video on the return flight path. Late in the afternoon, the last “Makkovik” line (middle line in Fig. 5) was surveyed; it had to be shortened due to the lack of ice and small floes that were again moving along with the long period swells. The last set of beacons was deployed along the outer part of the “Makkovik” line. Data examples will be presented from the “Makkovik” line, as its data were collected nearest in time to that of the RADARSAT image.

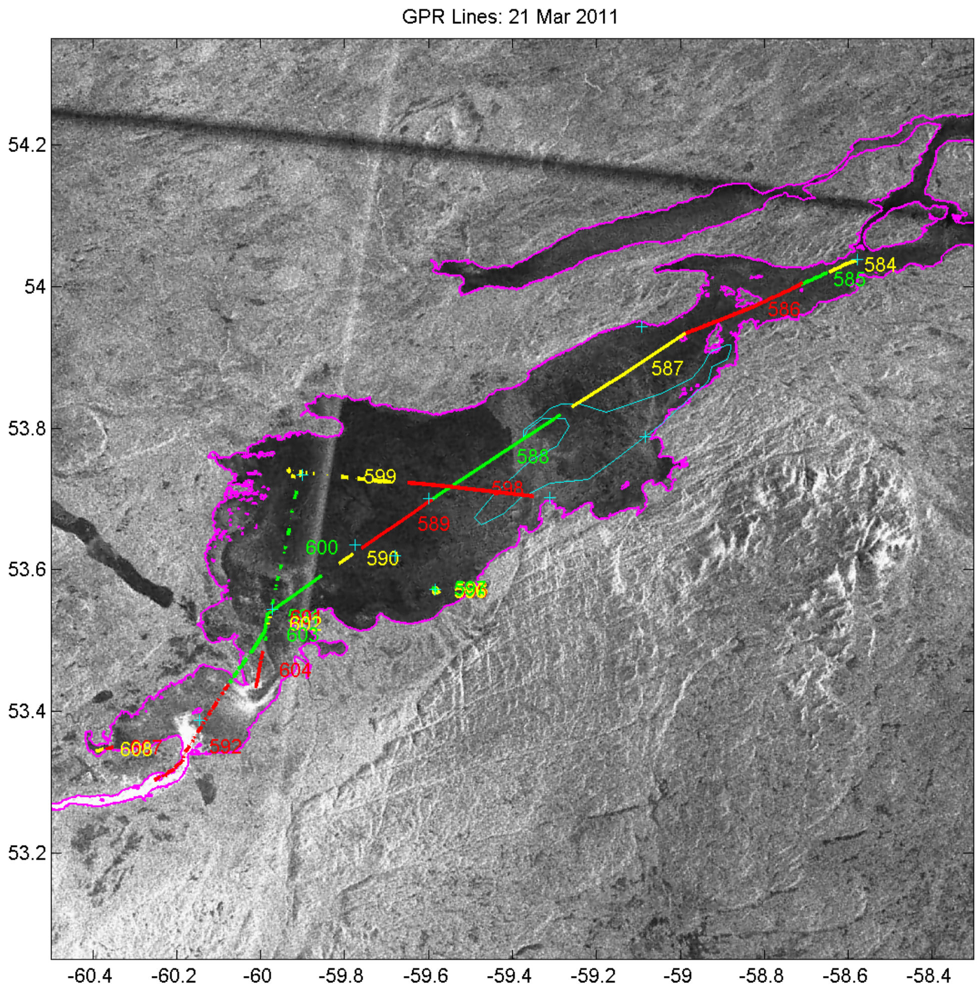

Fig. 6 Flight paths (with GPR file numbers) flown on March 21 overlain on a 100kmx100km RADARSAT-1 image of March 21. The long line from the coast to Goose Bay (GPR 584-592) was done in the morning and additional snow validation lines in the afternoon (© RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2011) - All Rights Reserved).

On Monday morning (March 21), a long EM-GPR survey line was flown along Lake Melville on the way back from the Labrador coast (Fig. 6). Snow thicknesses with the GPR sensor and surface freshwater layer thicknesses with the EM sensor were collected along the survey line to Goose Bay. After stopping at the hotel, on-ice snow thicknesses were measured at an on-ice station #596 (Fig. 6). Along a marked straight

45m long line, 36 snow thicknesses were measured with a snow staff, and the line marked with end bags was over-flown 6 times with the GPR. Larger snow thicknesses could not be found along the southern side of the lake from stn 596 to the start, and including the line #598 across the Lake towards the west, where an ice temperature beacon was deployed on March 17. The beacon was still in place and was later recovered by one of the helicopter pilots after a good performance test time series had been collected. A complete day-to-day report on the daily survey tasks and results are listed in the Appendix 1; the table below lists the flight lines along with the data file numbers collected during the 2011 survey.

Table 1. EM, GPR and video files collected during the Labrador ice survey of March 2011.

date	area	FEM File	GPR files	Video files
March 16	EM test flight	11001	To F512	----
March 17	Lake Melville	11002-11003	F514-F536	----
March 18	Lake Melville	11004	F537-F543	----
March 19	Lake Melville	11005	F544-F551	----
March 19	To/from Hopedale line	11006, 11008	F552-F558	F101-F105
March 19	Hopedale line	11007	F559-F562	F101-F105
March 20	To/from Mooring line	11010, 11011	F563-F565	F106-F108
March 20	Mooring line	11010	F567-F570	F106-F108
March 20	To/from Middle line	11012, 11013	F571-F572	F111-F118
March 20	Middle line	11012	F574-F579	F111-F118
March 20	Makkovik line	11014, 11015	F580-F583	F119-F124
March 21	Lake Melville	11017-11022	F584-F608	F125-F126

Weather conditions

Table 2 shows the monthly mean air temperatures for the winters of 2008-09 and 2010-11 at Hopedale, as well as the NCEP westerly surface wind components from the NCEP Reanalysis dataset (Kalnay et al., 1996) for the nearest grid point along the mid-Labrador coast (NOAA/OAR/ESRL PSD, Website (http://www.esrl.noaa.gov/psd/). As the table shows, the winter of 2010-11 was warmer than the winter 2008-09, which had near-normal winter air temperatures. The westerly wind component indicates the net direction the wind force acted on the ice; with positive values representing a wind force pushing the ice towards the Southeast along the Labrador coast. The lower westerly wind components such as seen in 2011-2011 in December and January relative to 2008-09 caused a reduction of ice being brought into the Labrador coastal areas from northern latitudes. During air flows from the south, warmer air temperatures occur, thereby also reducing the local ice growth. The short cold period in February of 2011 along with the large westerly winds could not offset the lack of ice growth and ice transport over the

November through January period, and resulted in reduced ice extent for the winter of 2010-11 relative to 2008-09.

Table 2. Monthly mean air temperatures at Hopedale and westerly wind component at 55°N, 60°W for the 2008-09 and 2010-11 winters.

	Air Temperature (ºC)		**Westerly Wind Component (m/s)**	
	2008-2009	**2010-2011**	**2008-2009**	**2010-2011**
Nov	-2.2	-0.1	3.39	4.67
Dec	-14.2	-2.0	6.65	0.43
Jan	-15.8	-8.4	6.47	2.98
Feb	-13.7	-16.8	4.02	6.99
Mar	-13.2	-11.1	3.48	3.79
Apr	-5.5	-6.1	2.64	3.52

Data Samples

Electromagnetic-Laser Ice Thickness

One of the aims of the program was to collect ice roughness and ice thickness data to identify ice features seen in RADARSAT imagery. Fig. 7 shows an HH RADARSAT-1 image of March 21 (1012Z) overlain with ice thickness data collected over the mobile pack ice off the Labrador coast between March 19 and 20. The northernmost Hopedale Line was collected on March 19 and the remaining southern three lines, “Middle”, Makkovik and “Mooring” lines, were collected on March 20, the day before the image was acquired.

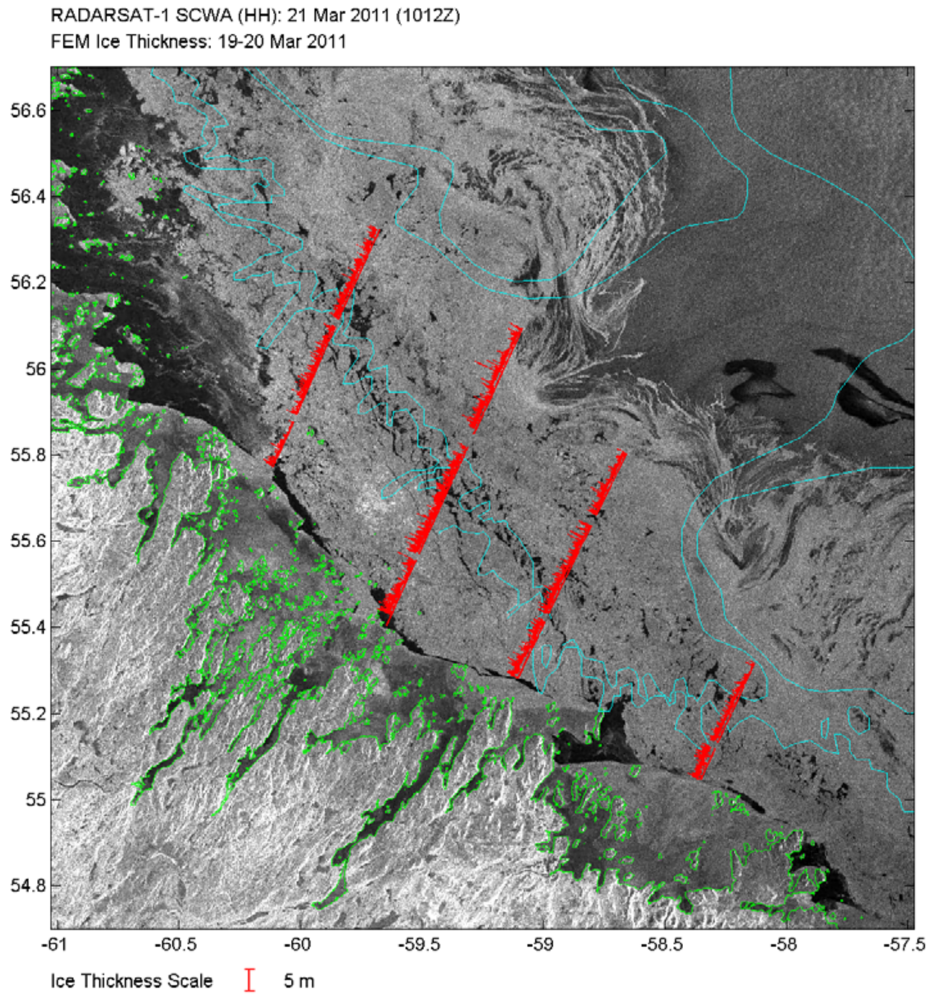

Fig. 7 March 21 RADARSAT-1 image overlain with ice thickness data collected on March 19 to 20, (© RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2011) - All Rights Reserved).

The two southernmost offshore lines were shortened due to the lack of concentrated pack ice, small floes and pack ice motion due to long period swells. The lines were not shortened because of helicopter range as was the case along the northernmost (Hopedale) line and for the 2009 survey lines.

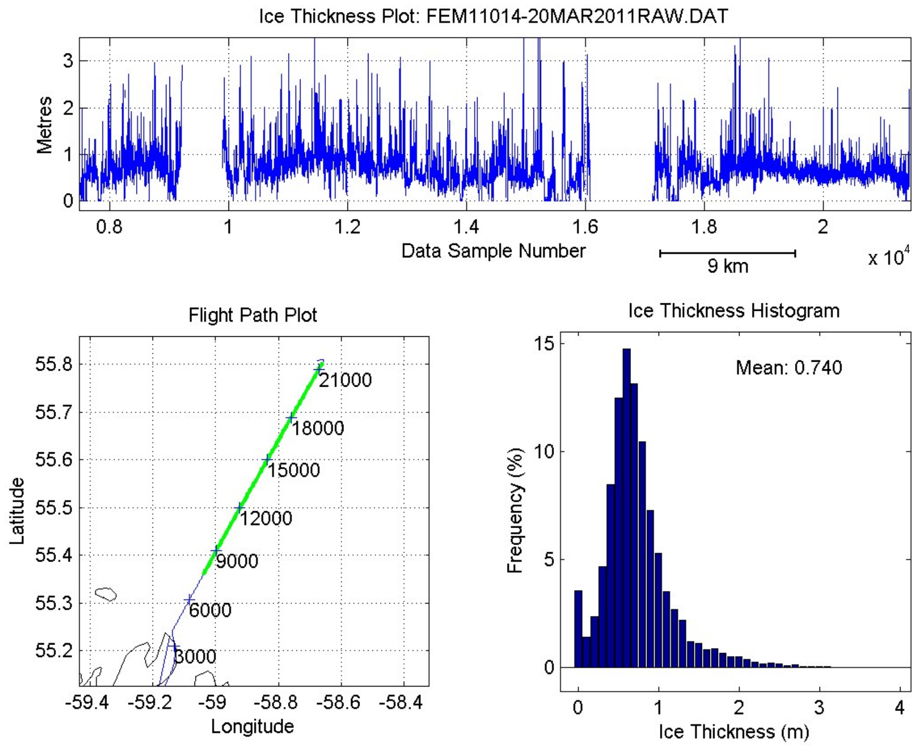

Fig. 8 Offshore mobile sub-section (~60km) of the ice thickness data from the "Makkovik" survey line. The green line in the map shows where the ice thickness profile data plotted and used to derive the histogram were collected, with the inshore end on the left and the offshore end on the right.

The images in Figs. 5 and 7 show several distinct SAR ice signature regions. Offshore there is a bright SAR homogeneous region, inshore of this is a region with a mixture of dark areas and moderately-bright areas. Farther inshore there are other bright regions generated by small scale pack ice surface roughnesses. Just before the land-fast ice area, several large dark areas appear representing open water and scattered frazil ice areas. The differences in ice thickness of these regions are hard to distinguish from the overlain ice thickness data in Fig. 7. They become clearer if one looks just at the enlarged ice thickness profile, as shown for the Makkovik line in Fig. 8. The two data gaps in the ice thickness profile are where the helicopter moved to 400ft altitude to obtain a "zero ice anomaly" reading to re-calibrate the sensor as well as provide a rest period for the pilot. The EM-GPR line was flown offshore so that the left side of the profile represents the inshore side and the right end represents the offshore side. The offshore end of the profile shows low variability in thicknesses and covers the offshore homogeneous bright area in the SAR image covered by the profile line (Fig. 7). Here the floes were very small and the space between them covered with frazil ice and wet snow blown in from the pack ice (Fig. 9).

Fig. 9 Small floes of up to 20-30m in length produced as the pack ice was broken up by long period waves.

Fig. 10 Large floes and leads in the middle section of the Makkovik line.

Inshore of this area of small wave-broken floes, the EM profile data shows larger ice thicknesses in ridges, an increase in ice thickness variability and the presence of large leads (sample number $1.75x10^4$ and $1.5x10^4$). The presence of leads within the middle of the pack ice can also be seen as dark areas in the image (Fig. 7) and a photograph of them is shown in Fig. 10. Some large floes have distinct parallel snow dune patterns.

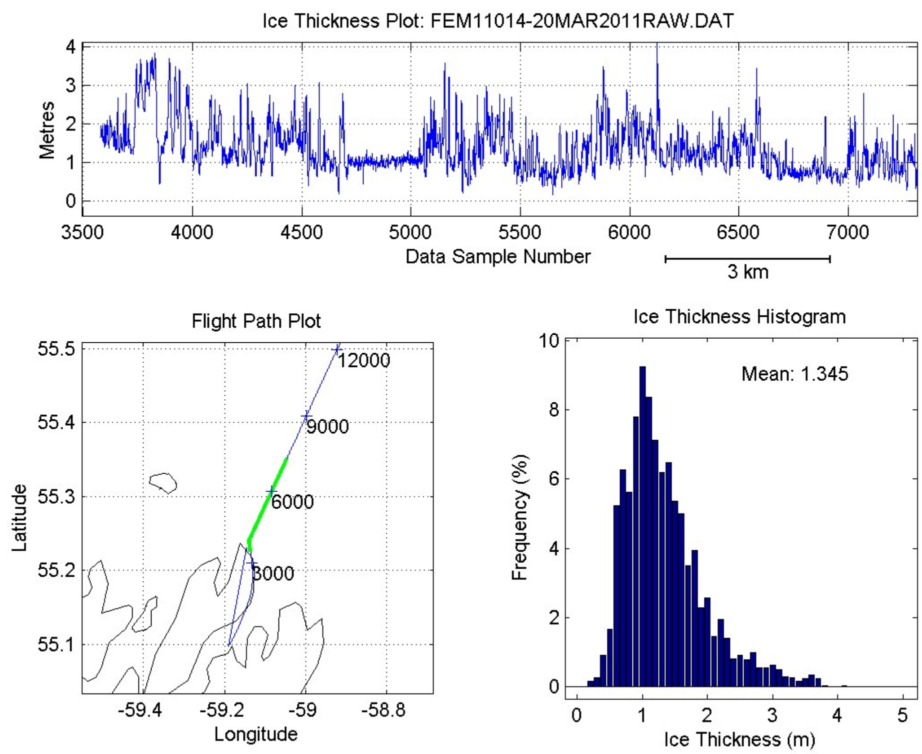

Fig. 11 Land-fast ice thickness sub-section (~20km) from the Makkovik survey line. The green line in the map shows where the ice thickness profile data plotted and used to derive the histogram were collected.

Fig. 11 shows the ice thickness profile section of the land-fast ice from the Makkovik line. A more extensive land-fast ice region is inshore of the "Mooring" line as can be seen in the Radarsat images (Figs. 5 and 7). The land-fast ice extent in early winter evolves (grows) in time in the offshore direction and is demarked from the mobile ice by shear ridges. The shear ridge that was present during the survey (Fig. 11) was at sample point $7.1x10^3$, inshore of this ridge older shear ridges can be seen within the profile at $5.9x10^3$, $5.1x10^3$ and $4.4x10^3$. Near the coast an ice rubble field reaches thicknesses of 3.5m ($3.7x10^3$ sample number). Most of the rougher land-fast is brighter in the SAR images than the un-ridged land-fast that is thinner; one 1.0m section can clearly be seen in Fig. 11 between sample numbers 4.7 to $5.0x10^3$. Compared to the offshore histogram (Fig. 8), the land-fast mean and modal thicknesses are larger in part due to its greater ice age, consisting of rafted floes but also of the deeper snow cover due to snow that was trapped in the rough land-fast ice. The land-fast ice along the Labrador coast shown in Fig. 12 has a very straight shear zone due to the constant southward moving ice cover. Large floes with distinguishable homogeneous ice features can be seen that were incorporated into the land-fast ice as it grew offshore. The near-shore part of the land-fast ice is the oldest and can be rough due to rafting. Snow thicknesses are large as what snow does falls (including during the early winter) normally remains trapped on the ice.

Fig. 12 Land-fast shear zone along the Makkovik survey line. Shore line is in the background and a second older shear zone can be seen where no large floes trapped within the land-fast ice appear.

The ice thickness histograms from the mobile offshore lines can be combined into a single ice thickness distribution for the mobile pack ice, covering the 220km distance sampled in March 2011 (Fig. 13). The mean ice thickness was 0.79m while the modal thickness (peak) representing the ice thickness most frequently encountered was 0.65m. No secondary peak at 3-4m was present. In comparison the ice thickness histogram sampled in the 2008-09 winter over the same four lines (Fig. 14) was very different. It captures two distinct modal peaks: the modal thickness of 1.1-1.2m in the offshore area and the modal thickness of 3.5m in the mid-area with large rough floes. The lines were longer and a total distance of 320km was sampled. A third minor peak although not statistical significant occurs at a thickness of 0.5-0.6m representing the inshore thin mobile ice region. The mean ice thickness of 1.68m for the mobile ice cover sampled was twice as thick as that sampled in 2011.

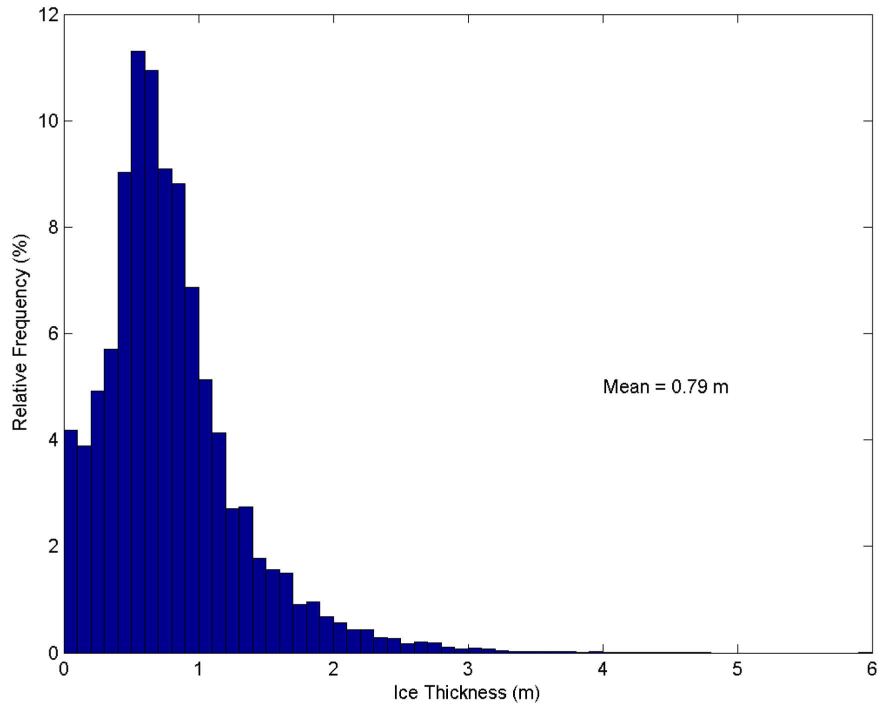

Fig. 13 Ice thickness histogram of the mobile ice sampled in March 2011 covering a total length of 220km.

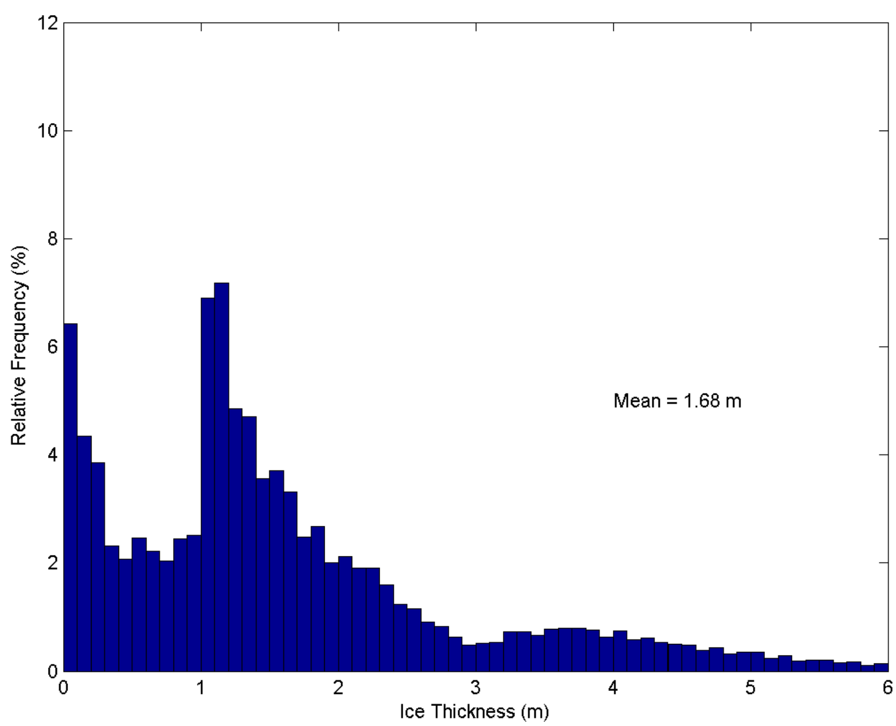

Fig. 14 Ice thickness histogram of the mobile ice sampled in March 2009 covering a total length of 320km.

Only some of the ice thickness profiles data have been shown along with a few still photos. The files used in the field are the "PIC rawfiles" and "PIC datfiles". They are used in the field to quickly plot the observations as line plots and histograms. The plots are e-mailed to other collaborators and the Canadian Ice Service for their inclusion in the production of ice charts. During the transcribing of the RAW files into "DAT" files, other files are generated in different formats and used in additional analysis and plotting. These files are all on the FTP site along with the "Ice PIC DAT" plots and other results and pictures that can be accessed through the DFO Maritimes "Seaice Website". http://www.mar.dfo-mpo.gc.ca/science/ocean/seaice/public.html.

GPR Snow Thickness and Video Data

Snow thickness data were collected with the Ground-Penetrating-Radar (GPR) during the low-altitude flights (Prinsenberg et al., 2011). GPR software developed for the 2010 Beaufort Sea survey was used to check the quality of data while it was being collected and to plot GPR snow thickness profiles covering approximately 1km of profile data sections. The file numbers of the GPR data collected on March 20 are shown overlain on the SAR satellite image of March 21 (Fig. 5).

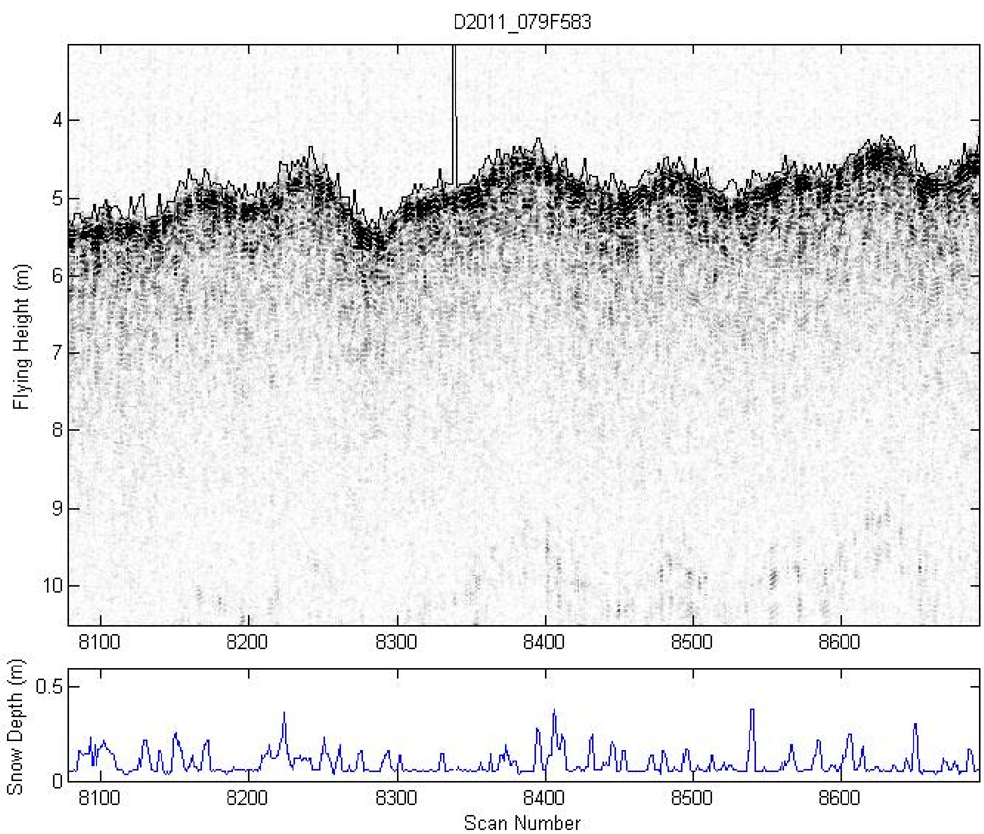

Fig. 15 Start of GPR line #583 showing ~1km of GPR-Laser profile and resulting inferred snow thickness profile. Left side is inshore and right side offshore.

As was the case for the EM data, the GPR and Video samples shown will cover mainly the observations from the “Makkovik” line. For the offshore bright SAR region, the EM (Fig. 8) and photograph (Fig. 9) show that this pack ice region consisted of small wave-broken floes with a modal 0.74m ice thickness. For this region, the GPR data (Fig. 15) from the start of the GPR line section (#583) shows that very little snow (mean of 0.10-0.20m) is present on these small floes and as expected was blown off the pack ice into leads. It is suspected that the regular 100-120m variation seen in the laser and snow echo distance to the helicopter is not caused by the helicopter motion, but more likely by the pack ice motion due to the presence of the long period swells that were observed when beacons were deployed on icebergs and ice floes. Other GPR profiles shown later do not show this regular variation in the laser height distance.

As shown in the mosaic (Fig. 16), some of the small floes still have snow dune patterns on them where snow is trapped by ice roughness. These snow dunes have thicknesses according to the GPR data of over 25cm (Fig. 15). However, much of the snow has been blown off the floes into the cracks between the floes, thereby stimulating the growth of slush ice that appears grey on the mosaic. Since the video mosaic width is 130m, most of the larger floes are less than 15m in size, not large enough in this mosaic on which the helicopter could land.

Fig. 16 Mosaic of 6 overlapping video frames (start frame #37929) showing the wave-broken floes during the return flight to shore and the small rough ice island fragment iceberg on which the helicopter landed to place a beacon on. The video frame width is 130m indicating that the floes are less than 15m in size and the iceberg is approximately 80m by 80m. The mosaic is from the same general area where the GPR data shown in Fig.15 was obtained.

Fig. 17 shows two mosaics of the pack ice along the Makkovik line. The video was started where the ice beacon was deployed on the tabular iceberg fraction as shown in the mosaic in Fig. 16, constructed by a time-consuming cut-paste routine. An automatic algorithm can produce mosaics very quickly from overlapping video frames; at present it outputs grey-scale images to reduce file sizes. The two mosaics start at frames 40676 and 40789, each having their own GPS lat-long-time stamp.

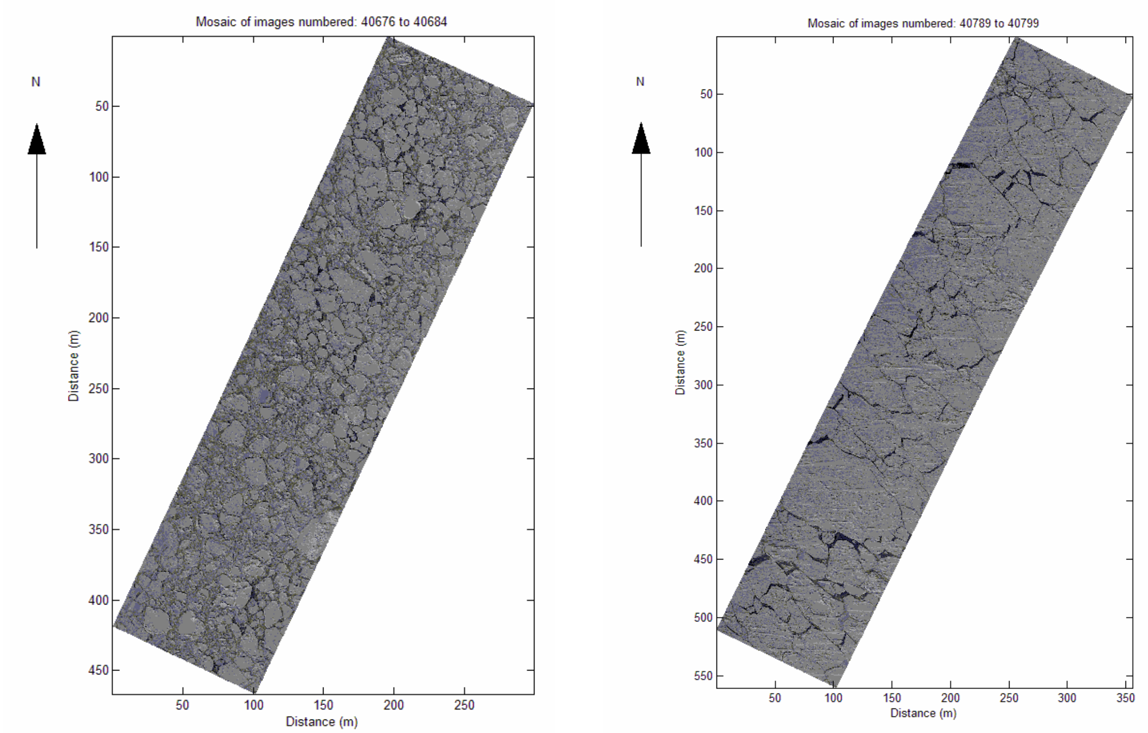

Fig. 17 Two mosaics from the offshore section of the Makkovik line showing the small floes (left mosaic) that consolidated into larger composite floes (right mosaic). The video frames were collected from north to south on the return flight to shore.

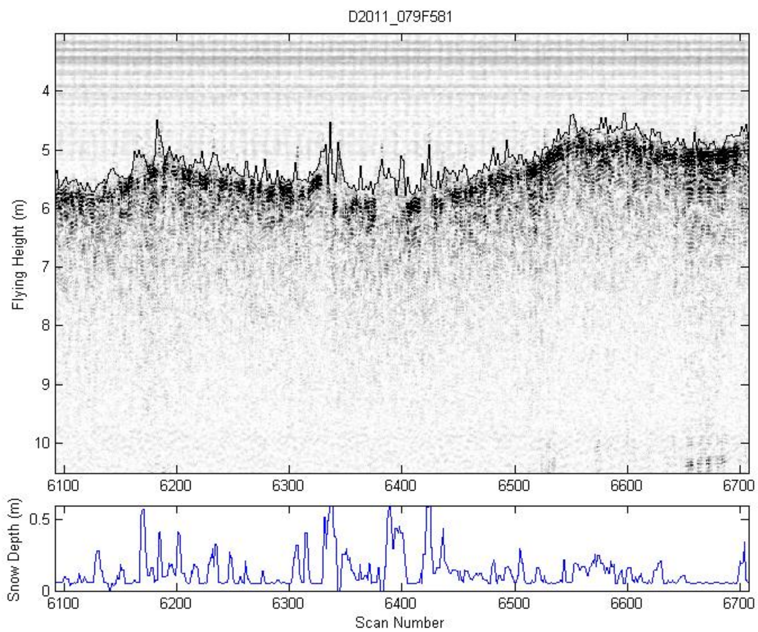

Fig. 18 Start of GPR line #581 in the middle section of the pack ice showing ~1km of GPR-Laser profile and resulting snow thickness profile. Left side is inshore and right side offshore. Snow dunes are deeper than seen offshore (Fig. 15) and a lead is probably present at end of profile (Scan number 6650-6690).

With the camera at 100m, each frame of the Mosaics (Fig. 17) represents a distance travelled of about 50 meters. The video line was started at frame 40617, so two mosaics are about 3km and 6km along the return (shoreward or southward) flight of the Makkovik line, and cover the first GPR subsection #583 shown in Fig. 5.

In the middle section of the pack ice, larger floes were present and separated by leads as shown in the photograph (Fig. 10); and covers the area in the images by the GPR line #581 (Fig. 5). A section of the GPR line is shown in Fig. 18. The flat area at the end of the snow profile probably represent a lead (Scan Number 6650-6690) as indicated in the EM profile plot at data sample number 11700 (Fig. 8). Some deep snow dunes of up to 50cm are present in the snow profile but also some areas lack snow, indicating that snow is continually stripped off the pack ice and only remains in areas of well established snow dunes that are probably anchored by rough ice topographic features made during ice ridging.

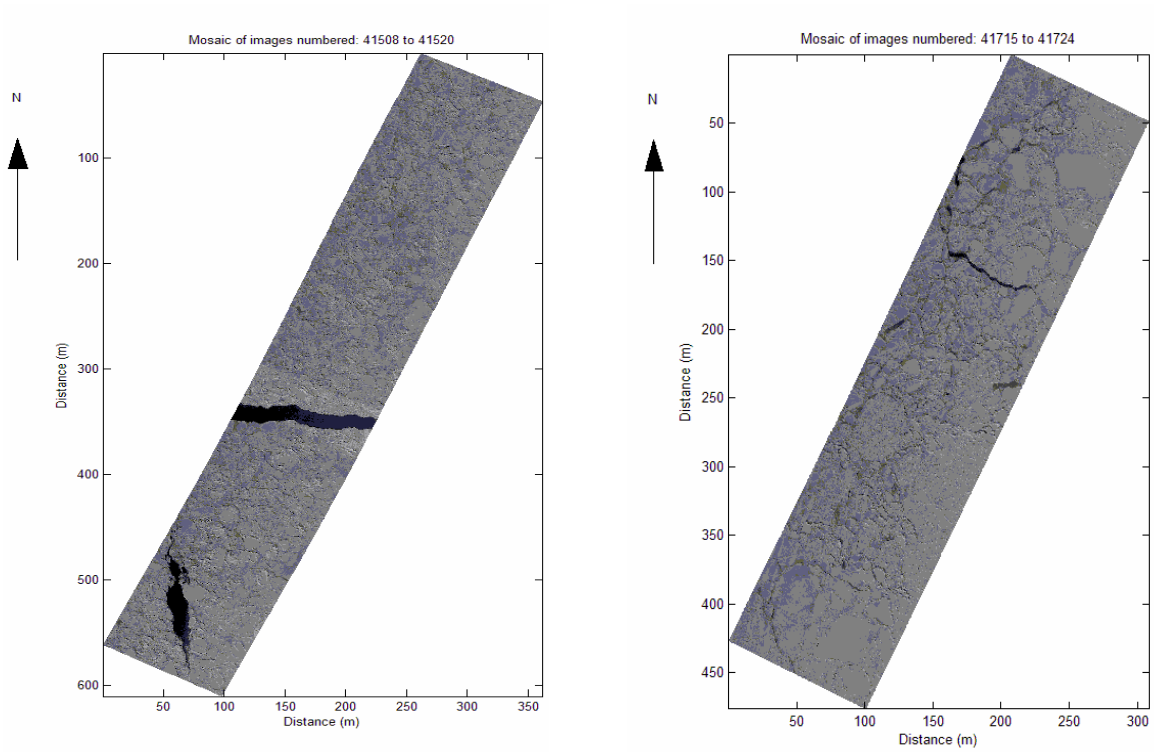

Fig. 19 Two mosaics from the inshore section of the Makkovik line showing the shearing the weakly consolidated large floes (left mosaic) in the middle of the Makkovik line, then thinner smaller floes near the land-fast ice (right).

The large weakly consolidated floes continued to be present along the remaining 50km of the Makkovik line to the land-fast ice edge (Fig. 19). As seen in the photograph of the land-fast edge (Fig. 12), the mobile ice near the land-fast ice consists of a mixture of large floes and very small floes that were generated by the shearing action between the mobile and land-fast ice as seen in the right mosaic of Fig. 19. The GPR data from this area is shown in Fig. 20. It shows a high variability of snow depths and some possibly leads where no snow was detected.

The land-fast (Fig. 12) shows large flat consolidated floes trapped within the rougher ice of the evolving land-fast ice. The EM ice thickness data from the land-fast also shows the existence of flat homogeneous thick ice between rough thicker ice.

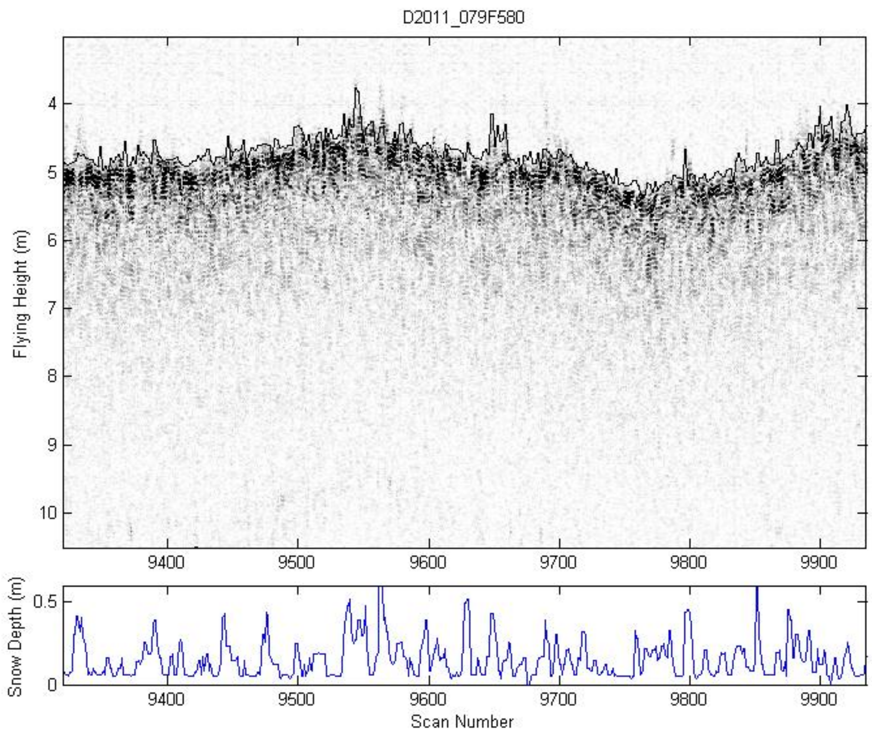

Fig. 20 GPR section (1.5km) from middle data file #580 (see location Fig. 5) representing the inshore large floe region along the Makkovik line.

Ice Beacon Data

ARGOS ice beacons provided by the Canadian Ice Service and Iridium-GPS beacons built by personnel at the Bedford Institute of Oceanography were deployed offshore on icebergs and nearby ice floes to monitor their relative drift patterns in response to ocean and wind forcing. On the first day (March 19) ARGOS ice beacons were deployed from the second helicopter by helicopter engineer Andrew Parsons (Table 3) and on the second day Iridium beacons by Ingrid Peterson (Table 4). While collecting EM and GPR data along the “Hopedale Line”, we searched for suitable icebergs to deploy beacons on. Relative to the 2009 survey very few icebergs were present. Just at the end of the Hopedale line, a tabular iceberg was seen north of the line on which the ARGOS beacon 12997 was deployed and an ARGOS beacon 16797 nearby on an ice floe. While collecting Video data flying to shore along the Hopedale line a second set of beacons were deployed on a pinnacle iceberg (12995) and nearby ice floe (11254).

Fig. 21 Ingrid Peterson deploying Iridium ice beacon on small pack ice floe on March 20.

Table 3: CIS ARGOS Beacons (deployed 19 March, 2011)

Deployment_Day/Month/Year Time(ADT) Argos/WMO_Number

1) 19/03/2011 1611 12997/44656 Tabular iceberg or ice island fragment, Hopedale line, 200m x 100m (Video), 5.3m High (FEM11007)
2) 19/03/2011 ~1630 16797/44657 Ice floe near 12997
3) 19/03/2011 1650 12995/44655 Pinnacle iceberg, Hopedale line, 100m x 100m (Video), 19m High (FEM11008)
4) 19/03/2011 ~1710 11254/44654 Ice floe near 12995

Fig. 22 Video mosaic of tabular iceberg or ice island fragment; video data taken from 122m height providing frame widths of 135m. The iceberg is about 100mx200m, has a freeboard estimated with laser of 5.3m. Argos beacon 12997 was deployed on iceberg on March 19, Video frame 34520.

Fig. 23 Helicopter on tabular iceberg or ice island fragment during deployment of ice beacon 12997 on March 19.

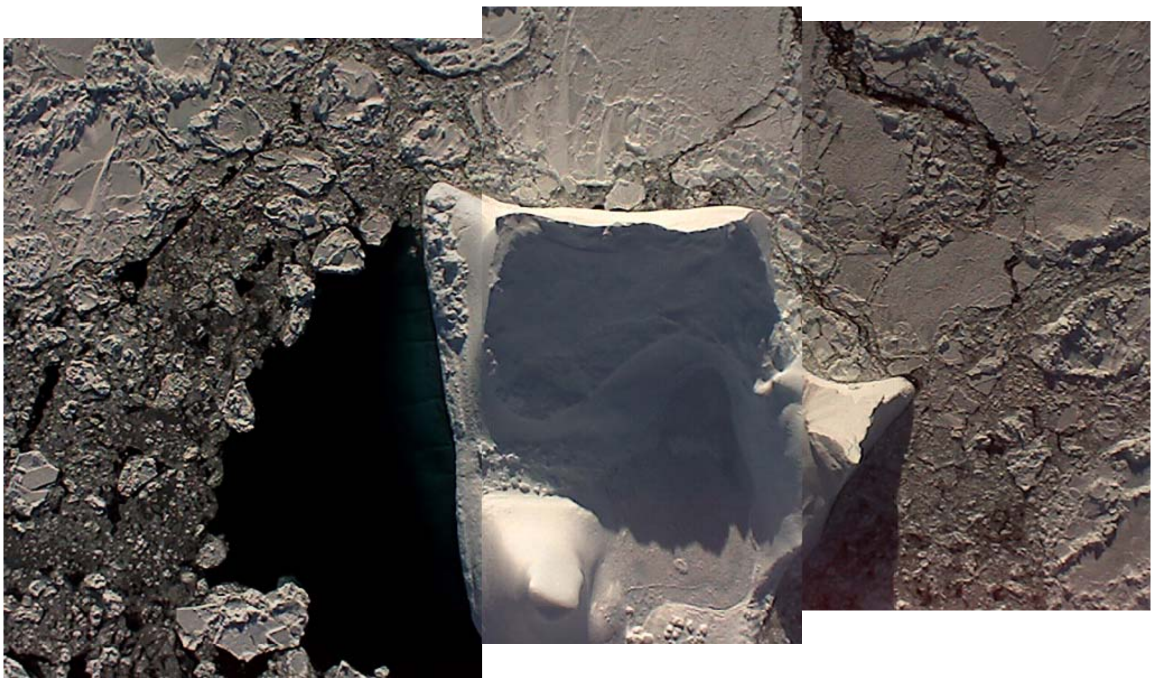

Fig. 24 Pinnacle iceberg mosaic from Video frames taken at a height at 120m providing frame widths of 132m (March 19). Pinnacle iceberg about 100mx100m. ARGOS ice beacon 12995 deployed on berg (Video frame 28393).

Fig. 25 Helicopter on pinnacle iceberg during deployment of ice beacon 12995, March 19.

Two sets of Iridium-GPS beacons were deployed on two low tabular icebergs or ice island fragments and nearby ice floes on March 20 (Table 4): one set at the end of the shortened mooring line and one set along the Makkovik line. It was hard to find suitable icebergs as there were not many present. Also the ice floes were very small near the selected icebergs. The iceberg at the end of the "mooring line" was approximately 160mx145m in size and the iridium beacon 2484860 was deployed on it. Open water was present downwind indicating the pack ice moved quicker than the berg (Fig. 26). According to the helicopter GPS while on the ice and iceberg, the berg moved at 1.2 knots and pack ice at 1.4-1.5 knots.

The last set of beacons were deployed along the Makkovik line; beacons 2489850 on a rough rounded iceberg just north of the end of the line and beacon 2483920 on a small probably multi-year ice floe (2.9m thick). The iceberg was moving at 1.5knots in a 3ft swell with a 6-7sec wave period. The ice floe was moving faster at 1.7 to 1.8knots. A mosaic of this iceberg was shown before under Video data (Fig. 16)

Table 4: BIO Iridium/GPS (deployed 20 March, 2011)

Deployment_Day/Month/Year Time(ADT) Iridium_Number
5) 20/03/2011 0936 2484860 Tabular iceberg or ice island fragment, Mooring line, 160m x 145m (Video), 4.5m High (FEM11011)
6) 20/03/2011 0955 2483860 Ice floe near 2484860
7) 20/03/2011 1430 2489850 Rounded ice island fragment, Makkovik line, 90m x 75m (Video), 7m High (FEM11015)
8) 20/03/2011 1450 2483920 Ice floe near 2489850 (probably multiyear, ~2.9m thick)

Fig. 26 Helicopter on iceberg during deployment of ice beacon 2484860, March 20.

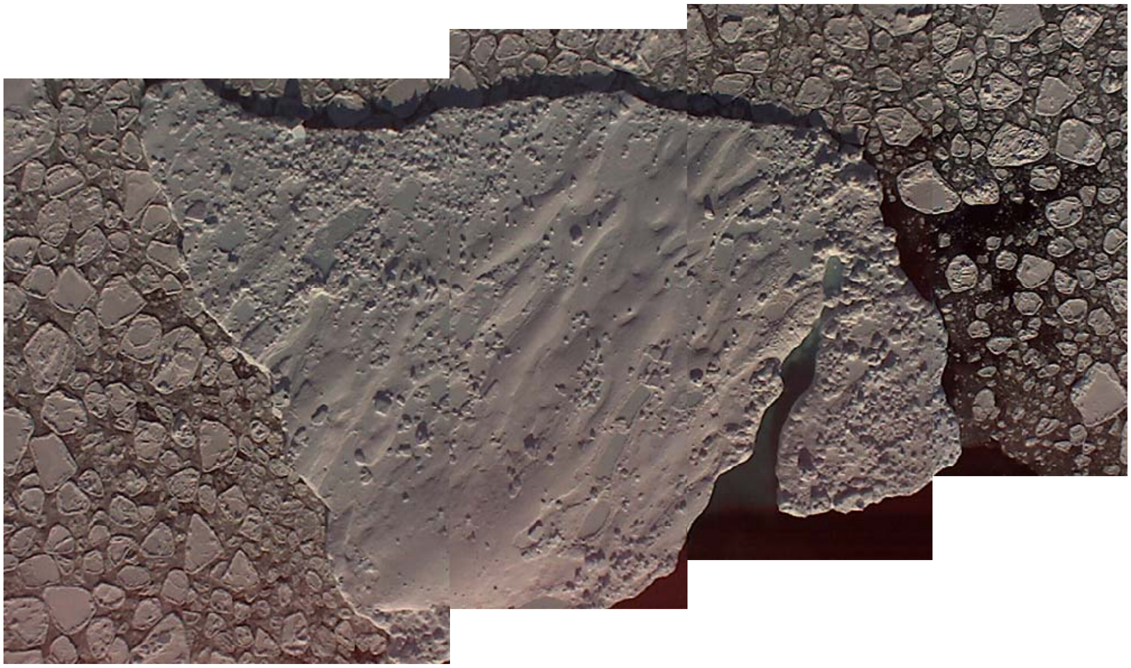

Fig. 27 Mosaic of small iceberg made of video frames taken at 133m height providing frame widths of 145m. Iceberg about 145mx160m; freeboard by Laser ~4.5m. Iridium beacon 2484860 (video frame 31610).

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Fig. 28 Helicopter landing on rough tabular iceberg or ice island fragment to deploy beacon 2489850, March 20.

Fig. 29 Helicopter on rough iceberg during deployment of beacon 2489850, March 20.

Fig. 30 shows the drift trajectories of the four beacons on icebergs and four beacons on nearby ice floes. The trajectories were very short as the beacons were presumably washed off the icebergs and ice floes due to large waves. The pack ice in 2011 was not as extensive as that in 2009, when it gave more protection to the inner pack ice and icebergs from open ocean surface waves. Only one beacon on an ice floe moved past and south of Hamilton Bank (Latitude 54°N). In comparison, the ice and iceberg trajectories observed in the winter 2009 (Fig. 31) were much longer, which some reaching the NE Newfoundland shelf. Of the 8 beacons, 4 moved past and south of Hamilton Bank.

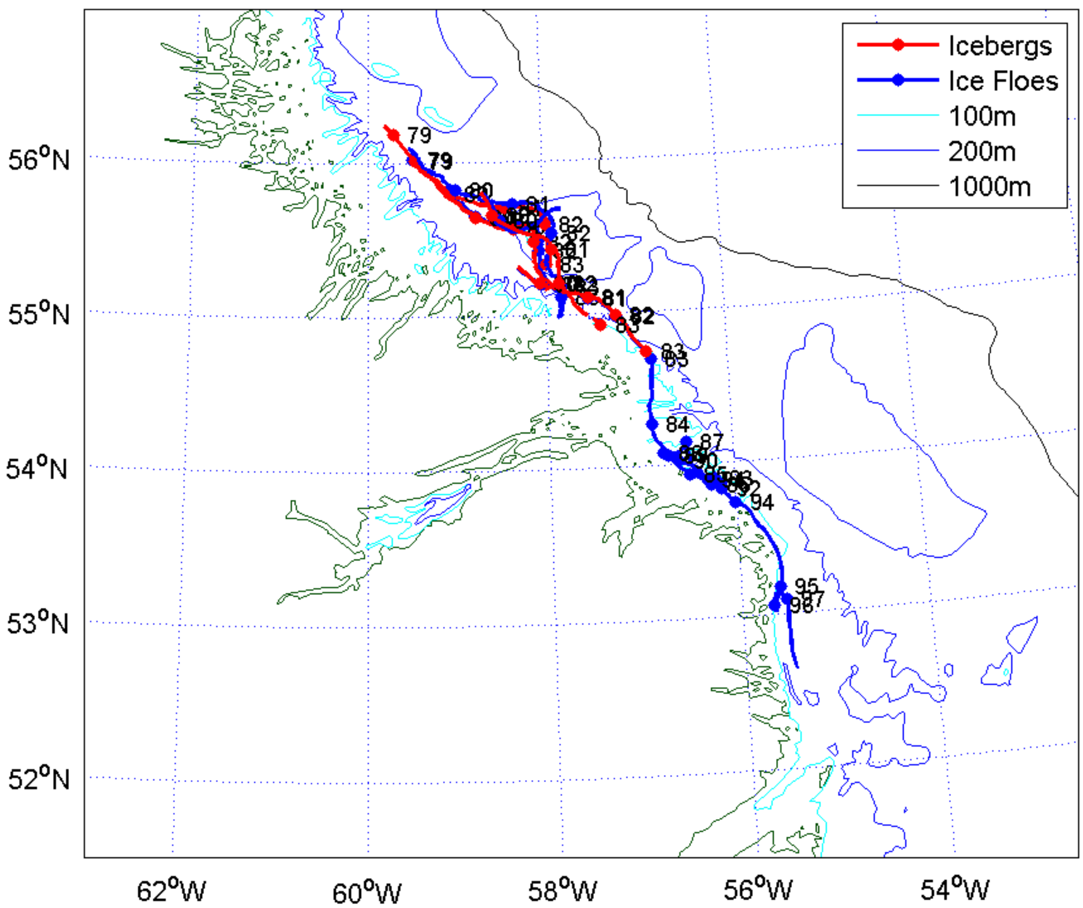

Fig. 30 Ice beacon trajectories representing iceberg (red) and ice floe (blue) drift patterns reported by beacons deployed off Labrador coast during the 2011 ice survey.

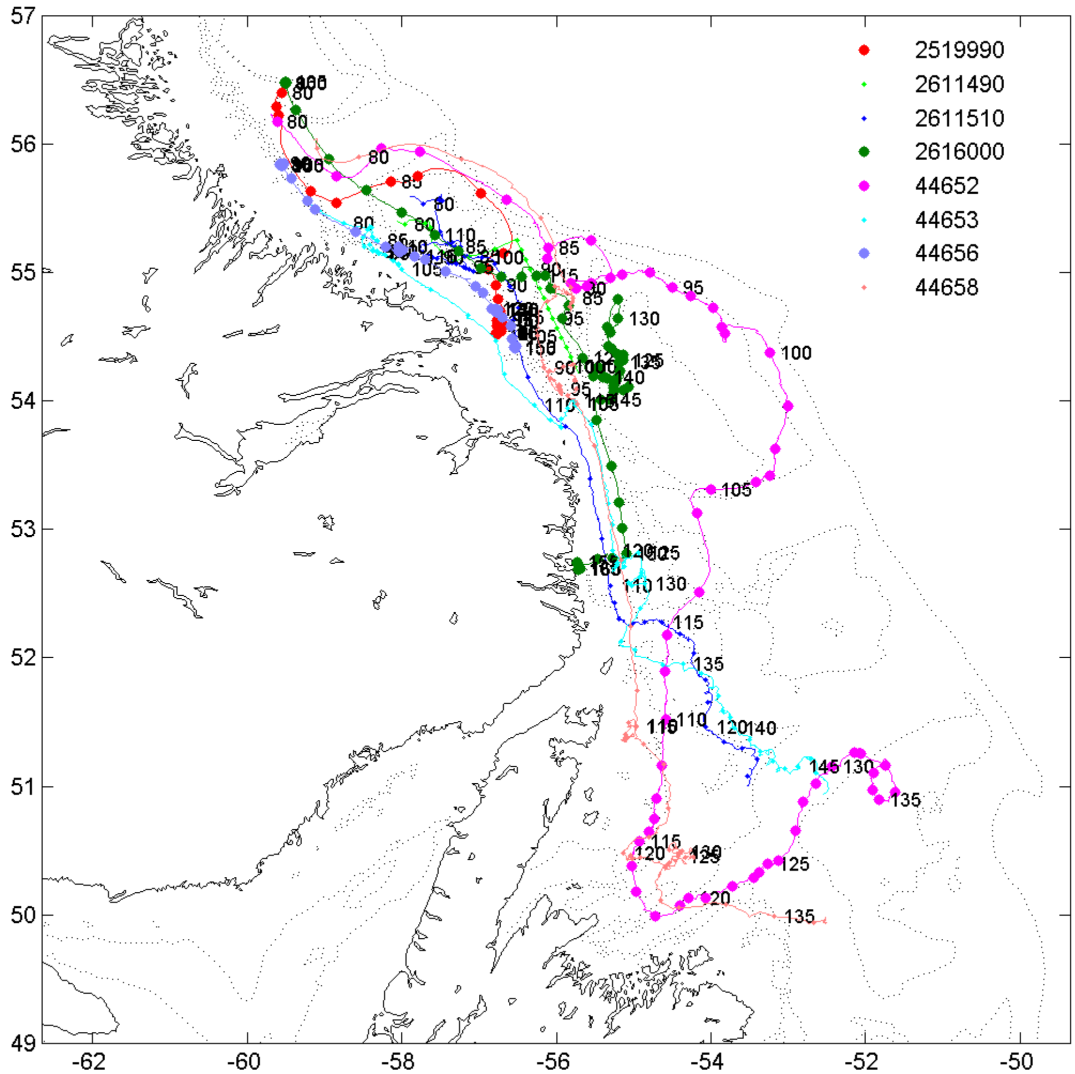

Fig. 31 Ice beacon trajectories representing iceberg (large dots) and pack ice (small dots) drift pattern reported by beacons deployed off Labrador coast during the 2009 ice survey.

Lake Melville On-Ice Data

GPR and EM data were collected over Lake Melville both before and after the survey off the Labrador coast. The flight lines with GPR data section numbers over Lake Melville for March 21 are shown before in Fig. 6. At several stations in the western section of the Lake (Fig. 32), an Idronaut Ocean Seven 304 CTD was used to collect CTD profiles of the top 30m of the water column; ice chip samples were collected to help assess the GPR capability of penetrating low-salinity ice. As found in 2009, the salinity of the ice cover increases from the head of the Lake (west) to the outlet of the Lake (east), due to the estuarine circulation driven by the Churchill River outflow at the head of the Lake.

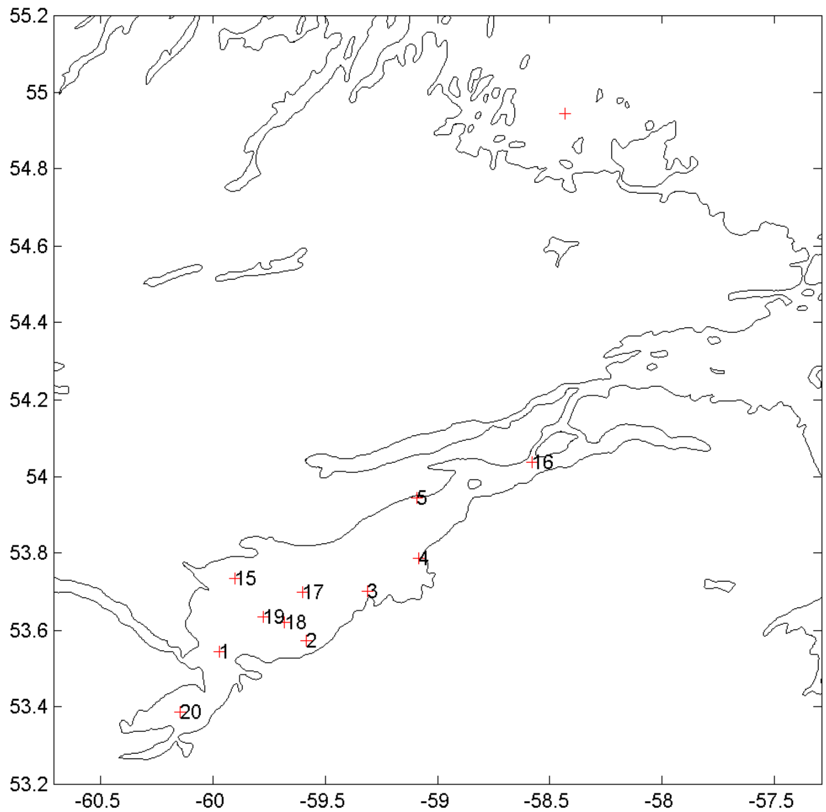

Fig. 32 Station map of Lake Melville. CTD profiles were taken only at stations in the western section of Lake Melville on March 21.

The locations of the on-ice stations were chosen primarily to measure the ice salinity where the GPR stopped seeing the bottom of the ice as one progressed eastwards into the Lake. The CTD profile from Stn. 20 is from Goose Bay, a small bay connected to western end of Lake Melville into which the Churchill River drains. The CTD profile shows both the down and up traces and hysteresis between the traces. It has a very sharp halocline due to the large runoff entering the bay. The surface layer is about 7.5m deep and its water is fresh (salinity of 0.0) and at freezing temperature (0.0^{o}C). Since this station is closest to the runoff source, it has the deepest and freshest surface layer of all the CTD profiles observed in the lake. The ice chips collected at three depths were all fresh (salinity of 0.0) indicating that at the time of ice formation, a freshwater surface layer was present. The Bay is connected to Lake Melville through a shallow entrance of 5-6m depth.

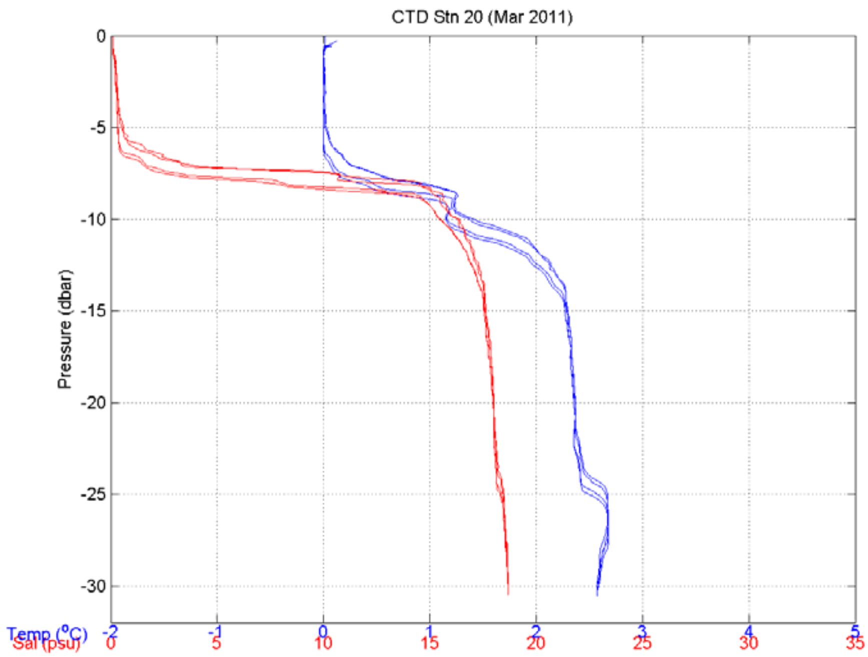

Fig. 33 Salinity-Conductivity-Temperature profiles in Goose Bay (Stn. 20), a small bay at the western end of Lake Melville into which the Churchill River drains.

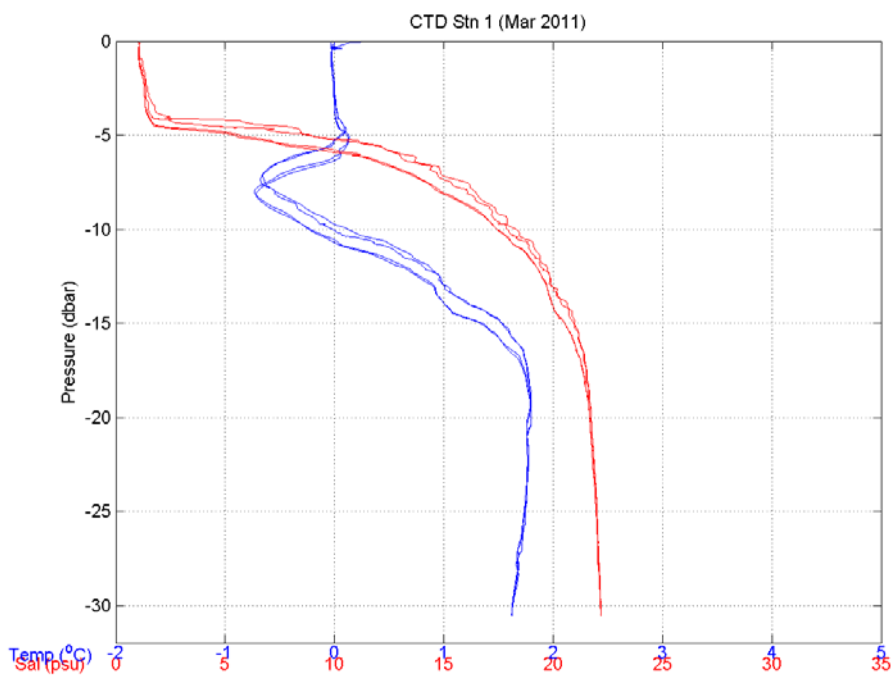

Fig. 34 Salinity-Conductivity-Temperature profiles at the western entrance to Lake Melville (Stn. 1) where the runoff of the Churchill River drains into Lake Melville.

Stn. 1 (Fig. 34) shows the water profile properties where the runoff surface layer enters into Lake Melville from Goose Bay. The lower part of the halocline is diffused and extends to 17m, representing continual mixing, possibly over shallow topographic features, between the freshwater surface mixed layer and the warm, saline bottom layer. The surface mixed layer depth has decreased to 4m, and some salt has been mixed into it (salinity of 1.5). Ice chip samples from March 17 all showed a salinity of 0.0, indicating the ice layer at the station was formed from the fresh surface water layer. Below this layer at 8m, the water temperature (-0.7°C) reaches a minimum, and is near the freezing point (-0.9 °C) for the salinity of 17. The salinity increases to 22 at a depth of 25m.

Moving farther east into Lake Melville (Stn. 19) the CTD profiles (not shown) were similar to that of Stn. 17 (Fig. 35). The surface mixed depth was 5m and a diffused lower pycnocline component with a temperature minimum was present. The salinity of the deeper layer (25m) remained at 22. The salinity of the ice varied from 1 to 4, indicating that during ice growth the surface water layer was mixed, and contained some of the salt content of the lower layer (Table 5).

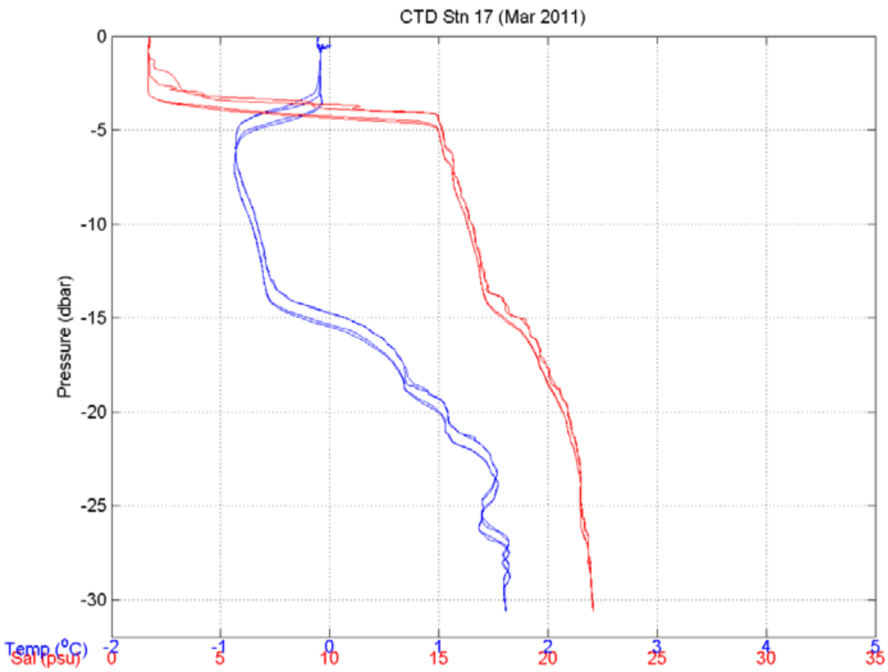

Fig. 35 Salinity-Conductivity-Temperature profiles in the centre of the western wide section of Lake Melville (Stn 17).

Table 5 lists the snow and ice data collected at stations in western Lake Melville; their locations are shown in Fig. 32. CTD profiles shown above were also collected at these stations. In comparison with the 2009 data, snow thicknesses on the lake were low, likely due to a recent rainstorm which removed the snow cover from the ice. Near-normal snow thicknesses of 40cm seen in 2009 were not encountered in 2011. Even though the winter of 2011 was warmer and thicknesses seen offshore were 50% less, ice thicknesses over the Lake were similar to those observed in 2009; possibly due to the reduced insulation of the snow cover. Most of them ranged between 65 and 79cm. The locations of the stations were chosen to monitor the ice salinity where the GPR stopped seeing the bottom of the ice as one progressed eastwards along the Lake.

Table 5. Lake Melville on-ice station data of March, 2011.

	Stn. 20	**Stn. 1**	**Stn.19**	**Stn. 18**	**Stn. 17**	**Stn. 2**
Date	March 21	March 17	March 21	March 21	March 21	March 21
snow depths (cm)	13, 13, 14, 15	6-8 mean 10-12 max	10, 11, 10, 10	6, 6, 10, 10	3-5	12, 12, 14, 12
Ice (cm)	76, 78	64, 46, 62	70, 69	70, 69	77, 79	65, 67
Ice Salinity (at 5cm)	0psu	0psu	3psu	2psu	1psu	0psu
Ice Salinity (at 25cm)	0psu	0psu	2psu	2psu	4psu	2psu
Ice Salinity (at 45cm)	0psu	0psu	0psu	0psu	1psu	1psu
surface water from CTD	2psu	0psu	1psu	1psu	1.5psu	2psu

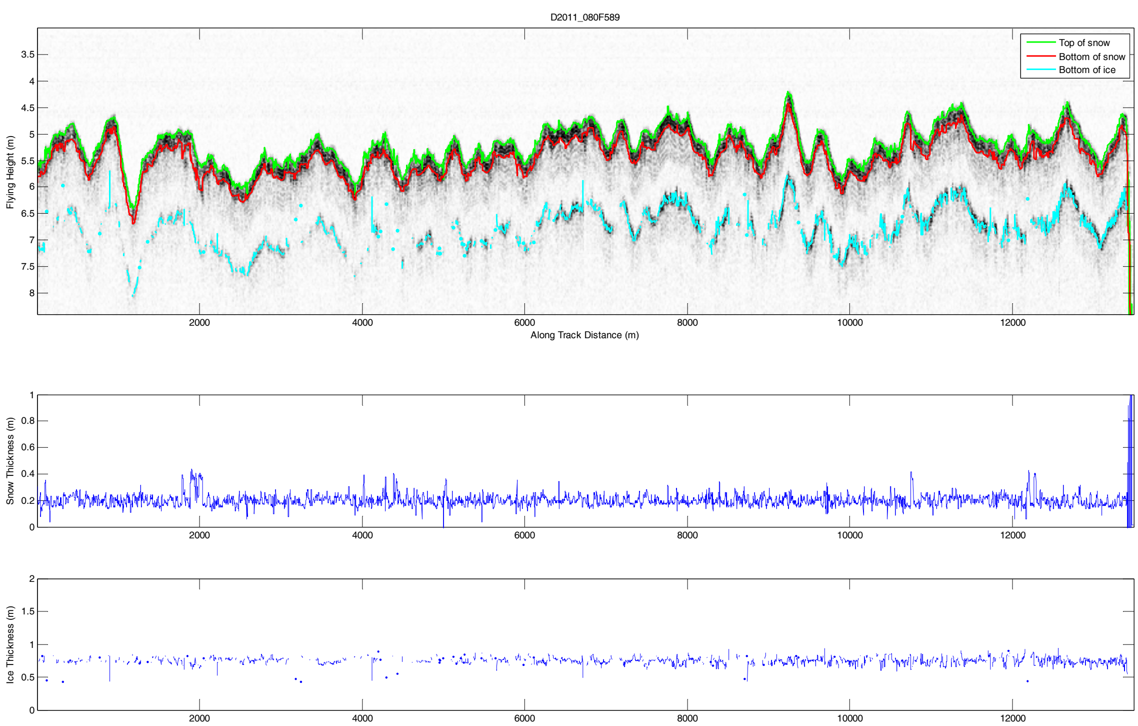

Fig. 36 GPR #589 line plot of snow and ice thicknesses from Stn. 17 (left side) to Stn. 19 (right side) showing the ice-water interface echo increasing in strength going towards the west from the centre of the Lake Melville (Stn. 17).

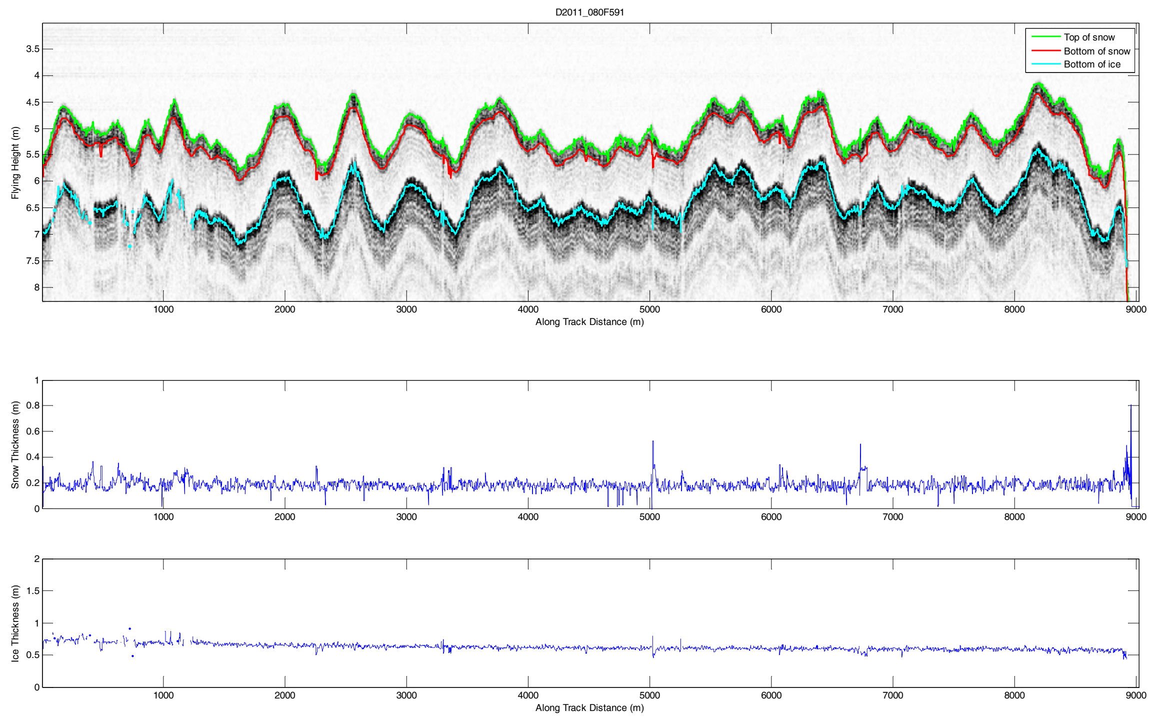

Fig. 37 GPR #591 line plot of snow and ice thicknesses from Stn. 19 (left side) to Stn. 1 (right side) showing the strong ice-water interface echo increasing in strength going towards the west along Lake Melville from Stn. 19 to the entrance to Goose Bay (Stn. 1).

As the Table 5 shows, the ice at stations 20 and 1 contain negligible brine since the ice salinities were 0.0. Therefore the GPR signal penetrated through it and could determine both the snow and ice thicknesses. Farther east into the Lake at Stns. 19 and 18, ice salinities at the surface and middle of the ice layer were higher (2-3), suggesting that this ice was formed from low salinity surface water that was mixed to some degree with the bottom saline layer. This kind of mixing is induced by fall storms which pass through before the surface freezes and insulates the water column from the further impact. Later in the winter as the runoff re-established a fresh surface layer under the ice cover, ice which formed at the bottom of the ice layer (e.g. at 45cm) did not contain salt. Continuing eastward at Stns. 17 and 2, the ice contained some salt throughout the ice cover. The surface values are low probably due the drainage of snow melt water during the rain storm in the fall.

GPR line plots covering the western half of Lake Melville show both ice and snow thicknesses (Figs. 36 and 37) derived from GPR echoes. The surface air-snow echo is also highlighted by the laser data. The plots follow the centre of the Lake where the on-ice data listed in Table 5. The GPR data was collected flying from east to west so that the salinity in the ice decreases along the flight path from the centre of Lake Melville at Stn. 17, then going westwards to Stn. 19 and on towards Stn. 1, the western end of the Lake. Fig. 36 is GPR #589 line plot of snow and ice thicknesses from Stn. 17 (left side) to Stn. 19 (right side) and shows the ice-water interface echo increasing in strength going eastwards along the Lake starting from the centre of the Lake (Stn. 17). Both the ice and snow thicknesses are very constant throughout the 14km long line profile, 75cm of ice and 20cm of snow. There may be a trend to thinner snow and ice thickness along the line (to the west) as the thickness do decrease in the follow-on line profile to the west shown in Fig. 37. The GPR #591 line plot of snow and ice thicknesses is shown in Fig. 37. It starts near Stn. 19 (left side) and covers 9km along the centre of the Lake to Stn. 1 (right side) showing the strong ice-water interface echo increasing in strength as the salt content within the ice cover decreases going towards the west along the centre of Lake Melville from Stn. 19 to the entrance of Goose Bay at Stn. 1. The ice and snow thicknesses are again very homogeneous and decreasing both slightly towards the west. The ice thickness decreases to 60cm and the snow thickness decreases below 20cm.

Farther east of these two lines the GPR is unable to see through the ice cover due to the presence salt in the form of brine channels. Fig. 38 gives a short example (~1km) of this, it is from the start of the GPR #598 line crossing at an angle across the centre of the Lake Melville (Fig. 6).

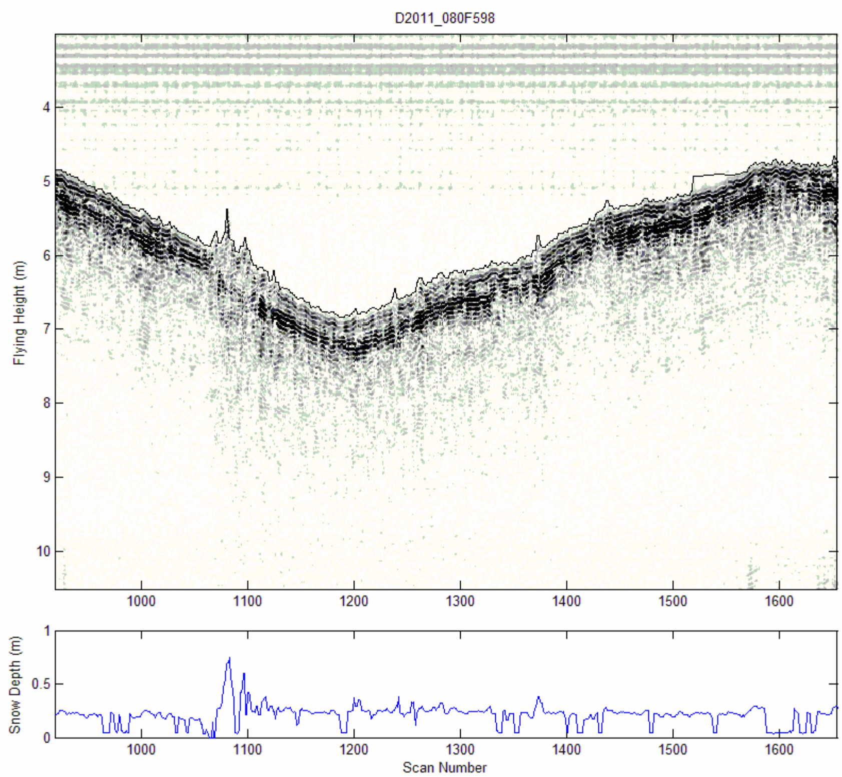

Fig. 38 GPR #598 line section plot (~1km) crossing at an angle across the centre of the Lake Melville where the GPR only monitors snow depths due to the salt within the ice layer. Location of GPR F598 data section is shown in Fig. 6, this data subsection is from the eastern end of the F598 line.

To validate the snow thickness measurements, areas of low ice roughness were sought with homogeneous but different snow thicknesses. The first area was near Stn. 2, with averaged snow thicknesses between 15 and 20cm. A line was marked by two backpacks along which snow depths were measured with a snow staff at intervals of approximately 1.25m over a total line of 45m. GPR snow thickness data were collected along two repeated race track patterns, and a criss-cross pattern to locate bags on the flight path plot. GPR files 593-595 were collected during the first race track pattern and are single files, GPR file 596 contains three passes over the snow line of the second race track pattern, and GPR file 597 contains the perpendicular lines.

Snow depths were measured every two steps along a line from SW to NE. A two-step interval represents about 1.25m and we had 37 measurements or 36 spaces for a total line of 45m. Below are the snow depths listed for each site separated by ~1.25m, the average is 16.5cm. The site #1 was at the SW side (helicopter side) and position #36 at the upwind NE side.

Table 6. Snow depth samples from western end of Lake Melville.

Site	snow(cm)	Site	snow(cm)	Site	snow(cm)	Site	snow(cm)
1	17	11	17	21	16	31	19
2	14	12	15	22	12	32	19
3	15	13	16	23	16	33	19
4	18	14	14	24	18	34	16
5	22	15	14	25	16	35	17
6	20	16	19	26	14	36	17
7	20	17	18	27	16		
8	13	18	19	28	16		
9	14	19	16	29	19		
10	14	20	14	30	16		

A total of six passes were made over the measured snow line; the approximate sample numbers along with the GPR file numbers are listed below (GPR080F597 criss-crossed the line at the end bag locations):

GPR File#	Sample #s
080F593	1430 – 1570
080F594	880 – 1030
080F595	1450 – 1600
080F596-1	1680 – 1830
080F596-2	4320 – 4475
080F596-3	7240 – 7390

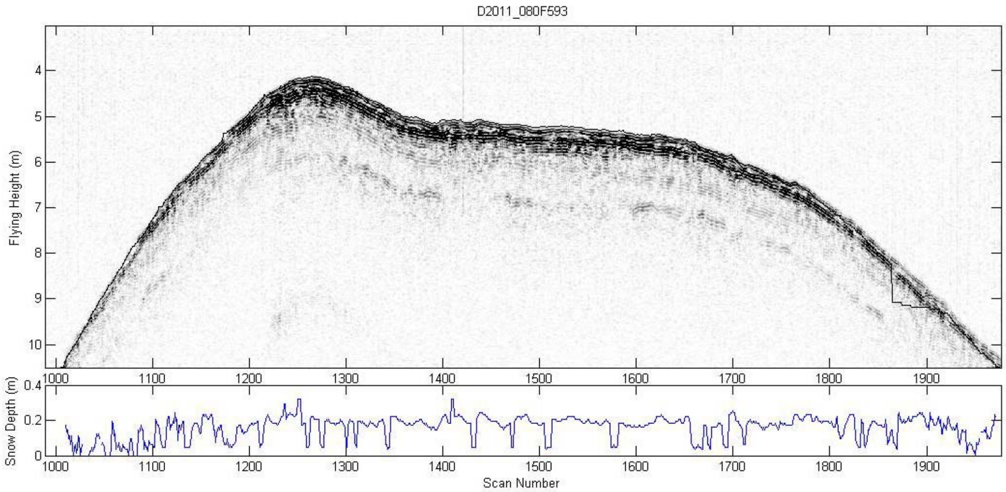

Fig. 39 GPR F593 line section plot (~1km) at the western end of Lake Melville covering the measured snow thicknesses shown in Table 6.

The measured snow depth line is between scan numbers 1430–1570, where the GPR shows snow depths of between 15 and 20cm, similar to the ground-truth values listed in Table 6. The other 5 passes over the marked line had similar snow depth values; the scan numbers where the ground-truth snow depths were measured are listed below Table 6 and their plots can be found on the Seaice Website.

Conclusion

This technical report described data collected during the March 2011 sea ice survey over the Labrador Shelf. No instrumentation delays were encountered during the survey of which 3 days were spent in Makkovik on the Labrador coast. March 20 offshore data of observed along the Makkovik line were highlighted in this report, since a SAR image was available on the next day to validate ice signatures seen in the image with observations.

The EM, GPR and Video data were collected from sea ice areas off the Labrador shelf and from Lake Melville. Data along flight lengths totalling of 430km were collected from the Labrador Shelf for both ice thickness and video data. Three mobile ice regions can be differentiated from the field observations and from the SAR image: the offshore homogeneous wave-broken floe region, the mid-shelf region with large floes and leads, and an inshore thinner ice region with both large and very small floes. Snow generally decreased with floe size. This is expected since snow on small floes is more likely to be blown into leads between the floes, or is washed off by waves during storms. The extent of the land-fast ice region was identifiable in the SAR image and ice and snow thickness data. The ice extent and ice thickness observed in 2011 were smaller than those observed in the same area in 2009; warmer and reduced westerly winds appear to account for the differences.

Ice beacons were deployed on small ice island fragments and nearby ice floes. Due to reduced ice extent and warmer air temperatures, the beacons and presumably the ice they were deployed on did not survived long and provided only short trajectories in comparison to those obtained in 2009.

Ice and snow thickness data were collected from Lake Melville during flights to and from the coast. The data show the existence of a surface freshwater layer below the ice cover, due to runoff from the Churchill and other rivers. Snow thicknesses were less than those observed in 2009. In the western end of Lake Melville, the ice contained no detectable salt, and appears to be formed from the fresh surface water layer. The GPR was capable of penetrating the snow and low-salinity ice, and provide their thicknesses. Farther east, the ice contained salt, and the GPR echo from the bottom of the ice slowly faded. The EM provided the depth of the surface mixed layer. The results indicate that for most of the Lake area, the total water column was mixed in the fall before ice formed. A freshwater surface layer evolved after the ice formed, thereby producing an ice cover with high surface salinities, and lower salinities near the bottom of the ice.

All raw and processed data, plots, reports and papers will be available through the "SeaIce" website: http://www.mar.dfo-mpo.gc.ca/science/ocean/seaice/public.html and through the website's data link to the DFO Maritimes' FTP site: ftp://starfish.mar.dfo-mpo.gc.ca/pub/ocean/seaice/.

Acknowledgements

The authors would like to thank Canadian Helicopters Ltd. personnel from Goose Bay for their assistance during the survey. In particular pilot Chris Rodway is thanked for the smooth flying at low altitude even in taxing weather conditions. Pilots Henry Blake and Dean Burry and engineer Dylan Pike are thanked for assisting with the survey work and making sure everything ran as efficiently as possible, and for deploying the ice beacons. This work was supported by the Canadian Ice Service (CIS) and Natural Resources Canada (NRCan) through their Program of Energy Research Development (PERD) and the Can. Space Agency GRIP programs.

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Appendix 1: Field Notes: Labrador shelf ice survey, March 2011

March 16, Wednesday

Scott, Ingrid in Goose Bay and Simon coming at noon from Toronto.

Test flight done in the morning with Scott and Ingrid. Pilot Chris Rodway. GPR files F511 and F512 near Goose Bay were fine and obtained with the old logging version while files 511 and 512 can be ignored (deleted) as all files prior to GPR 511.
In the afternoon we repacked beacons and equipment for the flight to the coast. But weather outlook is not good so we are staying in Goose Bay.

March 17, Thursday +3°C, cloudy no wind

10:00 Test flight was done at in marginal conditions.
Both Video and GPR worked with old programs. New programs do not send laser or GPS through; so the old programs were used. On tarmac Video laser reads 0.4m.
Short video file over land F097 then switched over to GPR. GPR worked on second try short file F514, BG at 10:09 and stopped GPR.

Short file towards Stn. 1 (GPR 515) but could not reach it (2miles out) due to lack of contrast and does need to fly too high. Turn to north coast (file GPR 518) and ended file at BG over land, turned back to Stn 1 (file F519) then turned towards Stn. 2, stopped GPR as we were too low (F521).

What is happening with the GPR display is that you can only see the last stored GPR file, not the file being logged. You pick the new file that is currently logging but the plot returns to the previous file. Later it shows that as soon as you call a plot the plot shown is there that is being logged but does not go past the time you call the plot (not really real-time plot (but close). And the second time you ask for a plot it goes back to showing the previous plot.

We could not reach Stn. 2 due to lack of contrast (4miles out logging GPR 522). The new version was run twice but nothing there. We tried to complete triangle again by going back to Stn. 2a along the north side of the Lake. GPR file 523 at 10:56, seals at Stn. 2a (15). Sampled GPR files 524, 526 and 527 in from Stn. 2a (15). Rain started on the way back to Goose bay at 11:45 and also wet snow.

14:45 all three of us going out with CTD equipment and ice temperature beacon.

Over land to Stn. #2a, beacon out at 15:08, very little snow in crusty patches, looks like rain destroyed the snow layer which was much less this year than normal. Ice chips bag #15 – 2ppt at Stn. 2a; Lat. 53 44.05°N and Long. 59 54.07°W. Ice thicknesses were 78 and 79cm, seals in the area towards the south.

15:24 GPR 530 and 531 to Stn. 2 than turned back to Stn. 2a as the GPR was not running until half way to St. 2; restarted the line after BG. 15:33 at Stn. 2a then heading south GPR532 to Stn. 2. For the line from Stn. 2a to Stn. 2 the GPR file 533 was on at 15:43. BG at Stn. 2 and going Stn. 1 file GPR 535.

Stn. 1 at 16:13 surface 64, 64 and 62cm, Ice chips at surface, 25cm and 50cm all 0ppt. Snow between 6-8cm and up to 10-12cm. Back to Goose Bay and at airport at 16:30.

March 18, Friday. Clear, light 15knts NW winds -8^{o}C

10:00 left for the Lake Melville but weather front is coming in from the NE.
We are flying straight to middle of the line between Stn.2 and 2a (now called Stn. 15). Short GPR file over inshore bay before BG. GPR 527 stopped before BG at 10:18. Very even snow depth was seen by the GPR with depths of around 15-20cm. We could not reach location and turned back just after passing over land spit with cabin. GPR 538 file was stopped before arriving at the BG at 10:28. After BG the GPR was logging file 539, it failed when going too high GPR 540 and needed to pull power and restart the whole system. We moved along shipping lane into Goose River and restarted GPR 542 at 10:41; after BG GPR 543 was logged. About one hour flight, the weather is following us into Goose Bay coming from the NE. Logging GPR appears to be okay when you "Stop Logging" before Back-Ground and "Start logging" after BG. Weather was bad the rest of the way in. Cancelled North Hotel rooms and registered at the Bed-Breakfast Hotel along the highway to the helicopter hanger.

Processed data at the BB hotel, looked at the GPR results, and picked stations we should stopped to take ice chips and CTD data. When flying back from the coast we should fly along the middle of the Lake to a station just east of the triangle made up of Stns.1, 2a and 2: 53.7^{o}N and 59.60 ^{o}W. Along GPR 523 ice chips at 53.625^{o}N and along line 532 at 53.62^{o}N and 59.68 ^{o}W. A CTD profile in Goose Bay itself to check if the mixed layer is at 8m or is there a flat bottom at 8m.

<u>Saturday March 19, 2011</u>. Northerly winds at 30knts, clear and -8^{o}C

9:05 left Goose Bay for the Labrador Coast, two helicopters Nolan Walsh flying as Chris Rodway is doing another job in the morning and will come later. Second helicopter on floats is flown by Dean Burry and has the engineer Andrew Parsons and Ingrid on board.

BG over Goose Bay then GPR 544, a second BG at 9:15 then GPR 545 to Stn. #1 (9:21) and then turn to #2 (546). Goose Bay has snow every where, I stopped GPR high up and then restarted is at low altitude without any troubles.
Several bands of rough ice were passed towards Stn. #2 starting at 5.8miles from #2 with flat areas in between. Blocks are very thin 10-15cm indicating early ice being rafted against the southern coast.

At #2 BG 9:35, GPR froze probably hit the start button twice? GPR was restarted at 9:41 now logging GPR 549. Stn. #3 of a point of land with very rough ice conditions, again thin ice blocks. End of GPR file 549 and BG just after #3, lots of pictures.
9:52 on to #4 logging GPR file 550, rough ice with flat areas regularly, GPS sensor was acting up, high mountains to the south. Lots of snow was seen in the area along with

rough ice. To stn #5 at 10:01 logging GPR file 551, thin blocks here also 10-20cm. Away from the southern shore some flatter ice areas intermittently with rough ice streaks was observed. Logging of PIC and GPR was stopped at northern side of the Lake and shut system down and continued over the mountains to the hotel/Airport where we unpacked the extra gear, had lunch and planned for the afternoon's sampling flights.

Saturday Afternoon

The helicopter were refuelled and we waited for Chris Rodway to change helicopters with Nolan. We are planning to first sample the Hopedale line and deploy ice beacons along it; following first the shore line from Stn. 9 to Stn.13.

13:52 at Stn. #9 rough shore mobile ice after BG at Stn. 9, 30mph head wind from the NE collecting GPR and PIC data; GPR 552 monitoring the coastal snow properties (including the ridging blocks within snow dunes. BG was done at 14:03 lots of pictures in this area, now collecting data on GPR file 553.

BG at 14:16 stopped GPR 554 file and restarted GPR 555 at 14:17, thin ice pictures. BG was done at the island at 14:24 with open water regions down wind of the islands. Between islands some land-fast ice at the start of GPR file 556. 14:26 young land-fast ice 20-30cm thick, large flat areas were seen. We turned to Hopedale for fuel. Closed and started GPR window without pulling plug and it failed; i.e. if you close window you need to pull the plug to restart GPR window. GPR 557 is an empty file, and re-started GPR 558 and sampling the increasing snow depths shoreward. At Hopedale at14:37 and fuelling up the two helicopters and providing the engineer Andrew Parsons with the ARGOS beacons, auger and deployment instructions (left at 15:17). GPR files 552-558 cover land-fast ice to Hopedale.

(Offshore line). Started GPR window at 400ft and this appeared to be fine (5:28), we were at the location where we sampled GPR on the way in. Started GPR just past inshore island where ice edge is 15:32 GPR 559. Island offshore and to the south. At 15:37 small open water areas and thin ice regions (20-30cm), running GPR 559. At 15:39 still thin ice, no real ridging was seen, it may be bright on the SAR as it has fine structure maybe old frost flowers covered with snow? No Icebergs, maybe one just south of the line farther along the line. BG done at 15:41 and starting GPR 560. Some thicker ice was observed of 35-40cm. GPR files 559-562 are offshore Hopedale lines. Another BG at 15:53 was done, now at GPR 561. Passing Berg just to the north of it and seeing a tabular iceberg north of the line. Stopped the line short at 16:04 and turned to tabular iceberg.

Stayed at BG level (400ft) height to the Tabular iceberg and turned the Video on F098 and criss-crossing tabular iceberg (but noticed video was not logging after we were done). Second helicopter deployed ARGOS beacon 12997 on tabular iceberg. Flew pattern around tabular berg to get an idea of its size in addition to what the PIC data will provide us. We looked a long time around the tabular ice berg for a pack ice floe on which to deploy ice beacon 16797. Flew Video at 400ft (F099) to second iceberg and landed near this three pinnacle iceberg to give another ARGOS beacon (12995) to the second helicopter (Video F099/33). Some low flying video was collected (8m at 16:36) at the end of F099. Deployed ARGOS #11254 on the ice floe (large but only 40cm thick) where both helicopter landed on the pack ice.

From pinnacle iceberg to Hopedale corner Stn. 13 at 16:59 running video all the way home F101 to F105. Frame with around 120m. Spot on video picture, but it slowly disappeared before we turned to Stn. 13 at 17:18 and arriving there at 17:40 and turning to Makkovik. In evening we started four Iridium beacons: 2483860, 2483920, 2484860 and 2489850.

Sunday March 20, 2011. Clear, -12°C, 25mph SE winds

At airport by 8:00 but helicopters needed to warm up and were ready by 8:30. We are going to sample along the "mooring line" Stns. 9-7-8; out collecting GPR and PIC data and back collecting video data. GPR file 563 should show rough ice between small floes. At 8:42 some open water patches occurred. At 8:43 rough ice occurred and ice up to 2m thick, Stn. 9 we did a BG at 8:44 to 8:46, the turned to Stn. 7 logging GPR 564 at 8:47. Here ice was rough, mobile and had cracks in it (no pressure). Ice was 30cm thick with ice blocks of 10-15cm. Moved over some land-fast ice at 8:50, BG done over open water. At 8:58 the GPR was logging file 565, other side of the open water area, no leads, at Stn. 7 at 9:08 and GB done, going to Stn. 8. GPR files 563-566 are land-fast lines and 567-570 are offshore line files. Inshore iceberg at the edge of temporary land-fast ice logging GPR 567 and it froze while doing the BG. Restarted after shutting GPR power, back logging 569; flat ice of 75cm and rafting to 2m, but very small floes. BG with large pancake ice, round with edges. Ice is moving in wave action and edge is near, short of mooring location (5miles). Stopped 9:33 (570) logging and going to a tabular type iceberg.

At the iceberg at 9:39, it showed open water down wind of it indicating the pack ice moved quicker than the berg. Berg moved at 1.2knts and ice at 1.4-1.5knts according the second helicopter GPS while on the iceberg and pack ice. Thicker ice (older) also has open water on lee side of the floe. Video (F106) used (9:52) over floe and iceberg, and continue to log Video data until Stn. 7. Wave period estimated of 6-8sec and up to 4ft in amplitude. Video all the way back to Stn. 7, stopped file Video F107 at 10:09. Restarted video file (F108) 10:10 to Stn. 9 and stopped at Stn. 9 at 10:38. We flew back to Makkovik airport for fuel and lunch.

11:15 going north to "Middle line" 9-11-12 and back.
At Stn. 9 we did a BG at 11:24, the arrow of laptop is jumping around. GPR started logging file 571, very recent ice growth was observed, 20cm and no ridging. At 11:33 we were over island and doing a BG 11:37 end file 572 over Stn. 11. We turned offshore; but I shut the laptop off to eliminate the jumping of the arrow pointer on the screen. Finally GPR data were logging normally on file 574 at 11:44. BG was done at 11:50 then GPR logged files 576 and 577, BG at 12:04 and GPR logging 578. Ice started to deteriorate and we stopped BG at 12:19 and went north to an iceberg. It was not a safe berg to land on.

So we turned back to Stn. 11 while collecting Video (F111) but aimed for a berg just north of the line. Large composite floes were seen (12:27) that probably consolidated overnight as we saw none the previous day along the Hopedale line. More large composite floes were seen at 12:29, but snow steaks were constant over each separate composite floe but different between floes. Farther inshore composite floes were smaller.

The tabular iceberg was reached; but it was the tabular iceberg with the beacon on it that was the previous afternoon along the Hopedale line, it drifted 33miles as did the Pinnacle berg were saw later again 15.9 miles farther to the SW (still the same distance apart).

Stopped the Video file 113 and started a new file 114 towards Stn. 11 at 12:46. Large floes and open water were seen on way to shore. Snow streaks on composite floes in all direction so floes do rotate elative to each other. Inshore there were more leads indicating ice was moving offshore as well as along shore. We were at 13:08 at stn #11 and turning to Stn. #9, changed to Video file F117. Reached the end of the line at 13:23 (Video file F118) and moved back to the airport (13:30).

13:55 To the Makkovik line: Stns. 9-10 and back. At Stn. 9 doing a second BG at 14:02 and GPR was started to log file 580. We were right away over mobile ice where composite floes with the snow steaks started. Ice concentrations were 9+ but some open water areas did occur. Later thinner ice with thin blocks occurred (15-20cm) were seen. And after some thicker ice, again thinner ice was seen at 14:08 including frazil ice areas but no ridging in the ice areas. Wind appears to be going down. BG was done at 14:11 composite floes of 50cm thick with snow streaks. Another BG at 14:23, some ice up to 1.5m but ice was deteriorating and smaller floes and wave motion starting to show up. End of the line at 14:23 and moved North to an iceberg while the video (F119) was logging data. GPR files 580-583.

This berg was moving in the wave pattern and was hard to land on. Second helicopter did land and we moved to a pack ice floe where the ice beacon on the pack ice would be placed later; note the video was on all the time so some are from floe and need to be erased. Berg was moving 1.5knots in a 3ft swell with a 6-7sec wave period. The ice floe was moving faster at 1.7 to 1.8knots. We left area at 14:56 with the video on file F120 towards land (Stn. 9). Floes near the berg was just being broken up by the swell motion (14:59), farther towards shore the floes were not cracked yet. Then farther inshore, the floes were smaller (15:13). Temporary shear line at 15:20 as mobile ice with cracks occurred farther inshore. End of line and logging of Video (F122) data at 15:22 and continuing recording on Video file F123 and F124 at airport at 15:30. In the evening we worked on data and the Lake Melville sampling plan of GPR and CTD locations and typing up notes.

Monday March 21, 2011 Clear -12^{o}C, light westerly winds

8:40 Both helicopters were packed and warmed up for the trip back to Goose Bay. Some video data were collected over the mountains on our way to Rigolet where we would start the survey line down Lake Melville. First BG was done at 9:30 and second at 9:38. After a short GPS/Video; the GPR was started at 9:31 logging file 586. Third BG was done at 9:50 and GPR file 587 was started, then after 4th BG logging GPR file 588 where large area of rough ice occurred (10:06) and then back to flat ice areas. 5th BG done at 10:18 and GPR file 590 was started. Files 591 and 592 were running over land to Goose Bay and saw Muskrat Falls were they are planning to put a hydroelectric Dam.

After Lunch at 12:15 we went back to do CTD profiles at Stns. 20, 19, 18, 17 and 2.

Surface sample are at 3-5cm depth, Middle depths are around 25-30cm and bottom depth at 50-60cm.

Stn. 20. Done by 12:35; ice thicknesses 78 and 76cm; snow depths 13, 13, 14 and 15cm. Station is in what is called Goose Bay proper before the water enters into Lake Melville.

Surface ice salinity	bag 19	0ppt
Middle ice salinity	bag 2	0ppt
Bottom ice salinity	bag 24	0ppt

Stn. 19. Done by 13:18; ice thicknesses 70 and 69cm; snow depths 10, 11, 10 and 10cm.

Surface ice salinity	bag 8	3ppt
Middle ice salinity	bag 21	2ppt
Bottom ice salinity	bag 20	0ppt

Stn 18. Done by 13:36; ice thicknesses 70 and 69cm; snow depths 6, 6, 10 and 10cm.

Surface ice salinity	bag 10	2ppt
Middle ice salinity	bag 22	2ppt
Bottom ice salinity	bag 18	0ppt

Stn 17. Done by 13:42; ice thicknesses 77 and 79cm; snow depths 3-5cm.

Surface ice salinity	bag 23	1ppt
Middle ice salinity	bag 4	4ppt
Bottom ice salinity	bag 1	1ppt

Stn 2. Done by 14:05; ice thicknesses 65 and 67cm; snow depths 12, 12, 14 and 12cm.

Surface ice salinity	bag 7	0ppt
Middle ice salinity	bag 9	2ppt
Bottom ice salinity	bag 12	1ppt

After ice chip and CTD sampling (14:05) we looked for flat snow features where we could sample a long constant snow depth line and compare it with GPR data. One was done at Stn. 2 where SP-IP measured snow depths along a line marked out by two backpacks. GPR was collected along two race tracks patterns in a row with a BG done in between and a criss-cross pattern to locate bags on the flight path plot. GPR files 593-595 were collected during the first the first race track pattern and are single files; while GPR file 596 contains three passes over the snow line of the second race track pattern and GPR file 597 contains the perpendicular lines.

Snow depths were measured every two steps along a line from SW to NE. A two-step interval represents about 1.25m and we had 37 measurements or 36 spaces for a total line of 45m. Below are the snow depths listed for each site separated by ~1.25m, the average is 16.5cm.

11	17	11	17	21	16	31	19
12	14	12	15	22	12	32	19
13	15	13	16	23	16	33	19
14	18	14	14	24	18	34	16

15	22	15	14	25	16	35	17
16	20	16	19	26	14	36	17
17	20	17	18	27	16		
18	13	18	19	28	16		
19	14	19	16	29	19		
20	14	20	14	30	16		

The site #1 was at the SW side (helicopter side) and position #36 at the upwind NE side.

A total of six passes were made over the measured snow line; the approximate sample numbers along with the GPR file numbers are listed below (GPR080F597 criss-crossed the line at the end bag locations):

GPR File#	Sample #s
080F593	1430 – 1570
080F594	880 – 1030
080F595	1450 – 1600
080F596-1	1680 – 1830
080F596-2	4320 – 4475
080F596-3	7240 – 7390

We flew over to Stn. 3 to see if snow depths were larger there but did not find them much different than at Stn. 2 (15:09). EM and GPR line was flown from Stn. 3 to Stn. 15 to check on the ice beacon, starting with GPR file 598. One BG was done in the middle and at each end; finished at 15:29, and a line was flown into Goose Bay. Snow started to appear along the line at 15:33 and the 15-20cm snow appeared at 15:36. Manage to freeze the GPR screen again and could not undo it by simply pulling the data USB plug, you have to stop the power to the GPR. Then restart the GPR logging program. Files 598 to 608 (15:51) were collected.