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Measuring the thicknesses of the freshwater-layer plume and sea ice in the land-fast ice region of the Mackenzie Delta using helicopter-borne sensors

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ABSTRACT

Helicopter-borne sensors have been used since the early 1990s to monitor ice properties in support of winter marine transportation along the east coast of Canada. The observations are used in ice chart production and to validate ice hazard identification algorithms using satellite advanced synthetic aperture radar (ASAR) imagery. In this study we evaluated the sensors' additional capability to monitor the freshwater plume characteristic beneath land-fast ice. During the Canadian Arctic Shelf Exchange Study (CASES) data were collected over the Mackenzie Delta in the southern Beaufort Sea where a buoyant river plume exists. Results showed that the electromagnetic–laser system could describe not only the ice properties but also the horizontal distribution of the freshwater plume depths that decreased in depth stepwise offshore as the flow of the buoyant plume was restricted by a series of ridge-rubble fields running parallel to the coast. Relative to the 2 m mean ice thickness, the plume layer depth varied from zero under mobile offshore pack ice to 3 m inshore of the third set of ridge-rubble fields.

1. Introduction

Sea ice is present for many months of the year off the Canadian east coast and in the Canadian Arctic. It represents a hazard to navigation but serves as a marine habitat for seals and polar bears. Information on ice extent, concentration, age and floe size is readily available to mariners and marine scientists on daily ice charts produced by the Canadian Ice Service (CIS). The ice charts are based on the visual interpretation of satellite Radarsat and Envisat ASAR imagery and augmented by airborne radar imagery and observations from helicopters and ships. The ASAR imagery is used to infer the concentration and dominant floe size of different ice stages of development, each having a particular thickness range. Information on ice deformation (rafting and ridging) can also be inferred from ASAR imagery, but this technology is not mature enough to include the derived results on ice charts. The deformed fraction of the pack ice is not only important for offshore marine operations but it can also represent a significant proportion of the total ice volume, which is one of the quantities required for estimating oceanographic freshwater and heat budgets. In coastal areas, severe ice deformations influence the near shore currents and the river plume distribution (Macdonald et al., 1995). The resulting shear ridges (Stamukhis) oriented parallel to the coast line cause the freshwater inflows to be retained inshore for prolonged periods, with potentially strong effects on the coastal ecosystem (Carmack and Macdonald, 2002; Galand et al., 2008).

Since the early 1990s, ice property surveys using helicopter-borne sensors have been conducted by personnel of the Bedford Institute of Oceanography of Dartmouth, N.S. in partnership with Canadian companies and other government departments (Prinsenberg et al., 2002; Peterson et al., 2003). Ice-plus-snow thickness and ice-surface roughness profiles are collected using a helicopter-borne electromagnetic (HEM) system. At the same time, mosaics are available from overlapping video frames

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collected with a video–laser system. The observations provide information on both level and deformed fractions of ice which are used to validate operational algorithms of the Canadian Ice Service (CIS) for inferring sea ice properties from satellite ASAR imagery. The information is also incorporated directly into ice charts produced by CIS and used in studies of ice–ocean–atmosphere interaction processes and marine ecosystems.

The field observations presented here were collected over the pack ice of the Mackenzie Delta in the Canadian Beaufort Sea during April and May of 2004 as part of the Canadian Arctic Shelf Exchange Study (CASES). The helicopter survey was conducted from the icebreaker CCGS Amundsen, which over-wintered in the land-fast ice of Franklin Bay located east of the Mackenzie Delta (Fig. 1). The objectives of the survey were to collect sea ice data for validating sea ice classification algorithms using Envisat ASAR imagery and to support CASES's marine habitat studies.

2. Instrumentation

During the 4-week field survey, sea ice thickness and ice-surface roughness were measured with a helicopter-borne electromagnetic (HEM) system, called the “Ice Pic”, built by Geosensors Inc. of Toronto, Canada. It consists of a cigar-shaped sensor package mounted on the nose of a BO-105 Canadian Coast Guard helicopter. The sensor package consists of an electromagnetic (EM) sensor with transmitter and receiving coils (transmitter frequencies of 1.7, 5.0, 11.7 and 35.1 kHz), a laser altimeter and an attitude sensor providing roll and pitch measurements. The EM transmitter coil produces a primary magnetic field that induces eddy currents in nearby conductors (seawater). The eddy currents in turn produce a secondary magnetic field that is sensed by the EM receiver coils. The electromagnetic sensor outputs along with roll, pitch and laser altimeter data are used in a proprietary nonlinear inversion code (© Geosensors Inc.) to estimate in real-time ice thickness and ice bulk conductivity. This code can also be used in post-processing to estimate seawater conductivity or seawater depth under appropriate circumstances. The inversion method is a descendant and refinement of techniques developed in the 1980s for exploration and geotechnical applications and is described in detail in Kovacs et al. (1987).

The laser altimeter data also provides ice-surface roughness profiles. The laser is an ADM 3-Alpha Geophysical unit built by Optech Inc. of Toronto, Canada and has a listed accuracy of 1.5 cm. The output sampling rate for the ice thickness and roughness data is 10 Hz, corresponding to a spatial sampling interval of about 4–5 m for the normal helicopter survey speed of 100 mph. The ice thickness and ice conductivity are estimated with a 2-layer model representing the ice and seawater layers by inverting the in-phase and in-quadrature EM components at two or more frequencies. The calculations are done in real-time on a computer strapped in the back seat of the helicopter and results displayed

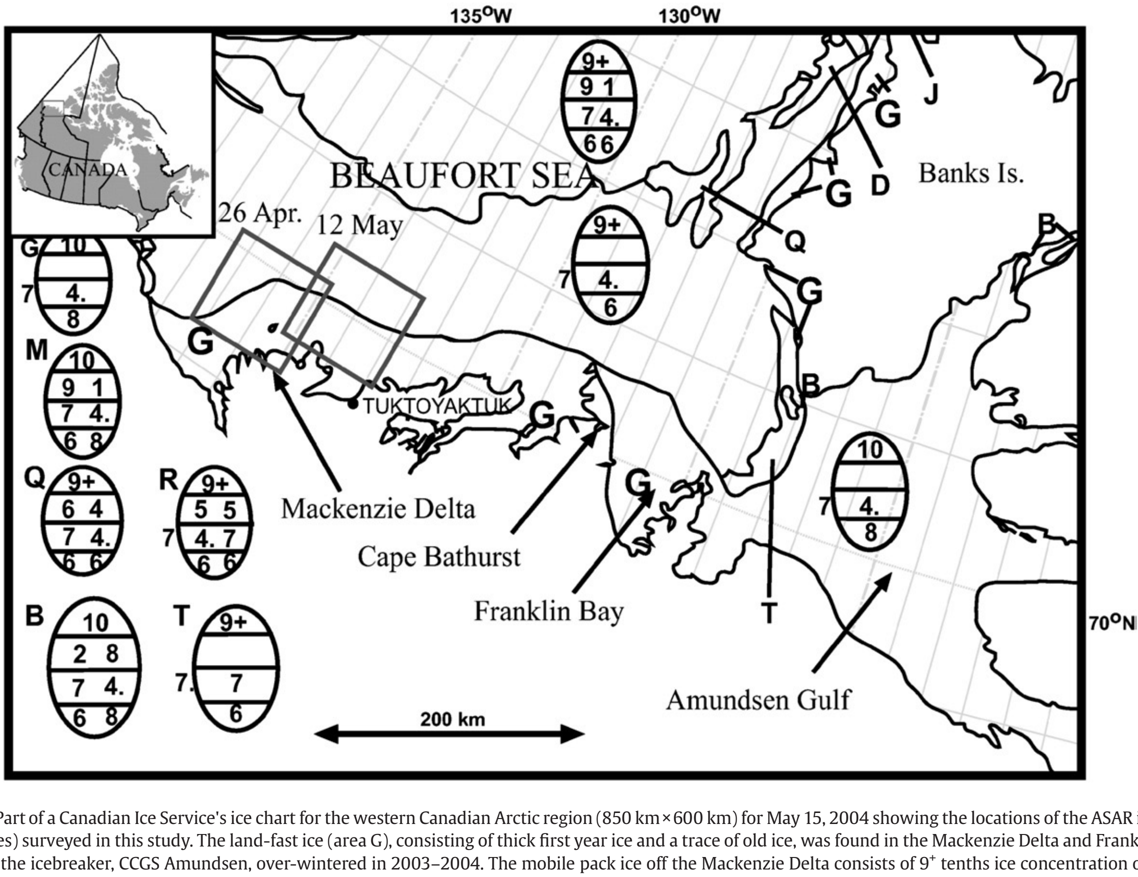

Fig. 1. Part of a Canadian Ice Service's ice chart for the western Canadian Arctic region (850 km × 600 km) for May 15, 2004 showing the locations of the ASAR images (squares) surveyed in this study. The land-fast ice (area G), consisting of thick first year ice and a trace of old ice, was found in the Mackenzie Delta and Franklin Bay where the icebreaker, CCGS Amundsen, over-wintered in 2003–2004. The mobile pack ice off the Mackenzie Delta consists of 9+ tenths ice concentration of thick first year ice (>120 cm).