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Various remote sensing approaches to understanding roughness in the marginal ice zone

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ABSTRACT

Multi-platform based measurement approaches to understanding complex marginal ice zone (MIZ) are suggested in this paper. Physical roughness measurements using ship- and helicopter-based laser systems combined with ship-based active microwave backscattering (C-band polarimetric coherences) and dual-polarized passive microwave emission (polarization ratio, PR and spectral gradient ratios, GR at 37 and 89 GHz) are presented to study diverse sea ice types found in the MIZ. Autocorrelation functions are investigated for different sea ice roughness types. Small-scale roughness classes were discriminated using data from a ship-based laser profiler. The polarimetric coherence parameter ρ_{HHVH}, is not found to exhibit any observable sensitivity to the surface roughness for all incidence angles. Rubble-ridges, pancake ice, snow-covered frost flowers, and dense frost flowers exhibit separable signatures using GR-H and GR-V at >70° incidence angles. This paper diagnosed changes in sea ice roughness on a spatial scale of $\sim$0.1–4000 m and on a temporal scale of $\sim$1–240 days (ice freeze-up to summer melt). The coupling of MIZ wave roughness and aerodynamic roughness in conjunction with microwave emission and backscattering are future avenues of research. Additionally, the integration of various datasets into thermodynamic evolution model of sea ice will open pathways to successful development of inversion models of MIZ behavior.

1. Introduction

Satellite records, starting in 1970s, and sea-truth observations of the Arctic have confirmed the rapid shrinkage in sea ice volume in the northern hemisphere (Nghiem et al., 2007; Kwok and Rothrock, 2009; Kwok and Cunningham, 2010; Stroeve et al., 2012, 2014). The perennial sea ice regime that dominated the Arctic is gradually turning into a seasonal ice regime resulting in more prevalent marginal ice zones (MIZs) (Gupta, 2014), which are the portions of the sea ice cover sufficiently near to the ice-free ocean such that interactions with the open sea result in the modification of the properties of the ice so that they are different from properties deeper within the pack (Weeks, 2010). MIZs are highly deformed and are known for enhanced dynamics and vertical exchange of energy, mass, and momentum between ocean-sea ice-atmosphere (OSA), termed OSA interaction (Claussen, 1991). Rough sea ice also acts as a habitat for a variety of animals that live on, within, and under sea ice (Stirling et al., 2004). Recent burgeoning interest in hydrocarbon exploration in the Arctic urgently requires better understanding of ice dynamics in the MIZ.

Recent studies have highlighted the occurrence of changing sea ice roughness, circulation, meteorological conditions, and OSA interactions throughout the Arctic (Esau, 2007; Hutchings and Rigor, 2012; Moore et al., 2014; Pizzolato et al., 2014). Satellite-based algorithms for the detection of multiyear ice are no longer applicable within a new ice regime, because these algorithms misinterpret the type of ice regime now actually found in the Arctic (Gupta and Barber, 2015). The thinning and shrinking sea ice cover in the Arctic necessitates further investigation of physical processes in the MIZs and improved understanding of how the physical roughness and enhanced OSA interactions in the MIZ affect the Arctic and global climate systems.

There is little knowledge of the processes that govern the spatial and temporal evolution of the physical roughness of the MIZ. Surface waves play a significant role in creating surface roughness; however, there are gaps in understanding how surface waves evolve within the MIZ as a function of fetch (Doble and Bidlot, 2013;

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Williams et al., 2013). More research is required to understand the role of wave roughness on the contributions of thermodynamic forcing in MIZ evolution. It is also important to understand how large period waves (swell) create roughness in the MIZ because large period waves can easily break up sea ice into fragments. The increased number of ice floes in the MIZ and their distribution respond to surface waves to create enhanced surface roughness (Lu et al., 2008). All these processes and dynamics create feedback mechanisms that become important in the emergence of a rough MIZ. Many of these processes can be understood only through sea-truth (*in situ*) observations; however, some scale-dependent processes can be better understood from satellite-based observations.

Various microwave observations of sea ice tell us its evolution mechanism, which forms the basis of our understanding of the evolution of associated physical processes in the MIZ. Satellite-based microwave observations not only cover large spatial extents but also provide useful data under all-weather conditions. Fully polarimetric active microwave remote sensing observations of first-year ice (FYI) and multiyear ice (both seasonally rough and smooth classes of each) at varying frequencies, particularly C-band (5.5 GHz), can provide detailed information on different aspects of each ice type and is still an evolving area of research (Geldsetzer and Yackel, 2009; Kim et al., 2012). Microwave polarimetry is a more recent tool and much less is known as to how this type of energy interacts with sea ice surface roughness (Wakabayashi et al., 2004; Peterson et al., 2008; Hendricks et al., 2010). Sea ice roughness affects passive microwave emission differently depending on microwave frequency, polarization, and sensor-surface geometry. There is still a perplexing ambiguity in deciphering dielectric and surface roughness contributions from the MIZ to the passive microwave emissions detected at the satellite sensor due to insufficient *in situ* data suitable for such work (Stroeve et al., 2006; Hong, 2010). Helicopter-based laser profiling and LiDAR (Light Detection And Ranging) imaging of rough sea ice further aid these investigations (Rivas et al., 2006; Haas et al., 2009).

This paper addresses to minimize this ambiguity by utilizing various ship-borne and airborne data with focus on physical roughness of the MIZ. There is a need for robust techniques to adequately detect and classify sea ice types and roughness within the MIZ. Polarimetric classification and development of associated techniques, e.g., polarimetric coherences are of much interest. The satellite-based passive microwave observations of the evolution of snow-covered FYI, and rapidly changing dielectrics and physical roughness of ice from spring to melt onset are anticipated to fill some gaps in understanding complex processes of the Arctic.

2. Materials and methods

2.1. Study area

The study area lies in Amundsen Gulf in the southern Beaufort Sea (Fig. 1). The Cape Bathurst Polynya forms in the area and hosts several flaw leads throughout the winter and the region becomes ice-free in the summer (Gupta et al., 2014a). In the present study, only the MIZ associated with FYI in the southern margin of the polynya is considered. During fall freeze-up, this area hosts a variable mix of ice types under various stages of formation (Fig. 2). The chosen samples for this study were selected as to cover larger surface variability and roughness types.

2.2. Ship-based laser profiler

To acquire surface roughness data, a moving ship-based laser profiler was used (Fig. 3c). The laser was mounted pointing vertically downwards (~7 m above the mean sea level) on the end of a beam, and was positioned ~3 m from the railing of the port side of the foredeck on the *Amundsen*. The laser wavelength is 905 ± 5 nm with a pulse width of 20.5 ± 5% ns and beam divergence 3.3 mrad ± 5% (1 mrad: 10 cm beamwidth per 100 m distance). The *RIEGL* (Horn, Austria) laser rangefinder model used is LD3100VHS-GF having average power of 640.0 ± 5% µW from a 50 mm wide aperture. Ninety data points are recorded at every 1.34 s. With a ship speed of 1.03 m/s (2 knots) the spatial resolution was 1.5 cm.

The photographs in Fig. 2a–c, and e–h were taken at an oblique angle from the port side of the *Amundsen* at ~8 m height using a hand-held digital camera after a given scatterometer scan; and Fig. 2d was taken at nadir angle on the ice floe at ~1 m height. In the present study, thin FYI types are considered (first stage: 30–50 cm – as per World Meteorological Organization nomenclature), which include snow-covered FYI, pancake ice, frost flowers and deformed FYI located within the MIZ.

Different sea ice types may have same rms height; therefore, different ice surfaces were distinguished by respective autocorrelation functions. The autocorrelation coefficient a_k, can be computed using the following formula,

$$a_k = \frac{\sum_{t=1}^{N-k}(x_t-\bar{x})(x_{t+k}-\bar{x})}{\sum_{t=1}^{N}(x_t-\bar{x})^2}, \quad k = 0, 1, 2, \ldots \tag{1}$$

where x is the sample height, N is total number of samples, t denotes serial number in the data series and k is increment.

2.3. Helicopter-based laser system

MIZ roughness data were acquired using a helicopter-mounted laser system, ADM 3-Alpha Geophysical unit, built by Optech Inc. (Toronto, ON, Canada) with a listed accuracy of 1.5 cm (Fig. 3b). It generated 905 nm infrared laser beams with a beam divergence of 5 mrad (0.28°). The sampling rate of the ice roughness data is 10 Hz corresponding to a spatial sampling interval of ~45 m (Nyquist 'horizontal' spatial frequency 0.125 Hz) for the normal helicopter speed of 46.3 m/s (90 knots) from 130 m altitude. The helicopter flights were made between April 16 and June 21, 2008 in horizontal profiles over the MIZ as the transition from winter to summer melt occurred. Twenty-one laser profiles were selected pertaining to different dates and locations over the ice. The surface roughness data of the MIZ were cleaned to retain only the ice surface heights. Thus, the sea ice roughness data from the MIZ contained surface height values from the ice surface only. For inter-comparison, four profiles during May–June were selected based on the data quality, temporal match between various datasets, and sufficient number of data points within datasets. Each profile contained numerous data samples lying between 277 and 58,449 with varying wind speed, thickness, and floe size. These data samples represent the realizations of a random process from an anisotropic rough surface representative of the MIZ in the southern Beaufort Sea. One-dimensional piecewise cubic Hermite interpolation was performed on the null and not-a-number (NaN) values in the entire data. Root-mean-square (rms) values of height were obtained for each data series.

A downward-looking video camera was mounted on the helicopter skids for capturing video image frames from 130 m altitude. The video frames can be composed to form mosaics to monitor ice. The video width was at a one-to-one ratio with altitude, which was used to manually estimate ice floe dimensions on video images.