Spatial and temporal variability of SAR backscatter signatures of coastal sea-ice types off the Lena River Delta (Laptev Sea)

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ABSTRACT. Field observations and SAR imagery of coastal ice off the Lena Delta (Laptev Sea) in 1996/97 show a strong zonation of ice types associated with gradients in ice dielectric properties and microstructure. Ice-growth and radar-backscatter modelling indicate that the distinct transition between ice of high mean, low variance and low mean, high variance backscatter corresponds to an increase in parent water-mass salinity above 2 to 5 ‰. High radar penetration depths allow for detection and mapping of bottomfast ice.

INTRODUCTION

Rivers assume an important role in the Eurasian and North American Arctic as sources of freshwater and dissolved or particulate matter discharged into the marginal seas. Supply and dispersal of freshwater furthermore have a strong impact on the thermo-haline circulation and sea-ice regimes in coastal and offshore waters. In turn, sea-ice processes in the river delta environment affect winter and spring freshwater dispersal as well as coastal evolution and hence constitute an important component of land-ocean interaction. Thus, water and sediment supply and alongshore transport in Arctic river deltas are strongly affected by the sea-ice zonation, such as the distribution of bottomfast ice along the 2-m topographic bench. Owing to the strong salinity gradients in the off-delta region, ice physical properties vary considerably across a zone of several tens to >100 kilometers width, encompassing the entire range of dielectric properties found in freshwater, brackish and ordinary sea ice.

In order to assess the value of SAR data for studies of these processes and coastal ice zonation, the present work focusses on the Lena Delta and adjacent sectors of the Laptev Sea as an exemplary environment. With an annual discharge of around 500 km^3, Lena river impact can be traced well across the shelf and into the Arctic Basin. Backscatter signatures of different coastal ice types have been derived from Radarsat SAR data in conjunction with ground measurements. Simulations with an ice-growth/salt-flux model forced with regional meteorological data were integrated into radar-backscatter modelling of different ice types, aimed in particular at explaining the distinct zonation and temporal evolution of backscatter signatures observed in the coastal environment.

STUDY AREA AND DATA SETS

Radiometrically calibrated Radarsat ScanSAR data covering the eastern Lena Delta and adjacent offshore region in the Laptev Sea (Fig. 1) have been analysed for the period October 1996 to July 1997. In this contribution, the discussion will be restricted to winter data of "cold" ice. Extensive sea-ice and hydrographic data sets have been collected in the fall of 1994 and 1995, with additional near shore observations from early winter of 1996 [1]. An ice-growth/salt-flux model [2] was driven with daily-mean meteorological data from the Tiksi weather station (Fig. 1) to derive time series of ice thickness and salinity, temperature and brine volume profiles through the ice cover.

SPATIAL AND TEMPORAL VARIABILITY OF SAR BACKSCATTER SIGNATURES

The SAR imagery reveals a distinct zonation in the coastal ice cover off the eastern Lena Delta, with a belt of high-backscatter ice (winter mean $\sigma^o = -14.7 \pm 1.7$ dB) of 20 km width lining the coast between the Bykov and Trofimov channels of the Lena (Fig. 1). This coastal ice exhibits a narrow spectrum of backscatter coefficients (Fig. 3), in contrast with the sea ice further offshore (winter mean $\sigma^o = -19.5 \pm 3.5$ dB). Along the coast, the high-backscatter ice (such as in sub-region D1, Fig. 3) is mostly confined to stretches neighbouring on the major river channels. The transition to offshore ice coincides with a set of pressure ridges following the 10-m depth contour. Its southern boundary, north of sub-region H, is less well defined.

While the mean backscatter coefficient for the offshore sea ice (Fig. 3, sub-region A1) and the high-backscatter coastal ice (Fig. 3, sub-region D1) remains at a near constant level throughout winter, coastal ice in shallow water exhibits a significant drop in the signal with time (Fig. 3, parts of sub-region G1, with $\sigma^o = -18.0 \pm 2.5$ dB in shallow water areas).

In explaining the zonation and temporal evolution of backscatter signals, and in particular the decrease of σ^o in shallow areas, the gradients in surface water salinity are of great importance, since they control the salinity and hence the dielectric properties of the ice cover (Fig. 3, right column).

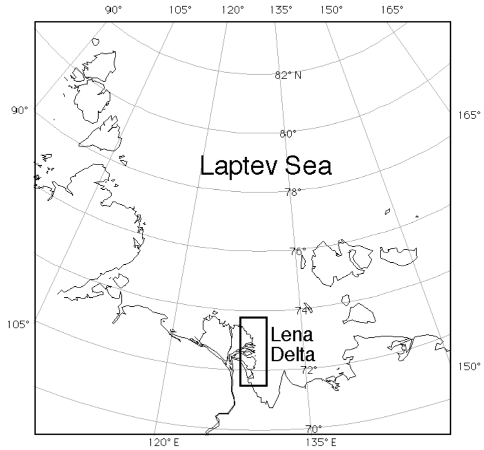

Fig. 1: Study area and location of SAR scenes (box).

Field measurements carried out in October 1995 and November 1996 show that the distribution of high-backscatter ice generally coincides with that of freshwater or low-salinity brackish ice (with salinities smaller than 1 ‰), characterized by layers of sub-mm to mm-size gas inclusions. The offshore sea ice beyond the 10-m isobath is more saline and lacks prominent gas inclusions. Freshwater discharge from the major river channels reduces surface water salinities to below 2 to 3 ‰ in the adjacent stretches of shallow water (<10 m deep). The diffuse transition from high-to low-backscatter ice north of sub-region H corresponds to a distinct change in under-ice surface water salinity from 6.5 ‰ at point S1 to 2.5 ‰ at S2 to 0.9 ‰ at S3 in November 1996 [1]. Furthermore, the highest backscatter ice in the river channels and in sub-region G1 (Fig. 3) has the lowest salinities with values mostly below 0.1 ‰.

Ice thickness modelling and comparisons with hydrographic charts indicate that the significant reduction in σ^o corresponds to bottom freezing of the fast-ice cover, similar to observations made on tundra lakes in the Alaskan Arctic [3]. Comparisons between tundra lakes in the Lena Delta and the coastal ice cover also indicate great similarity in backscatter statistics of these ice types. The ice further offshore is part of the broad fast-ice belt that covers the southern Laptev Sea. Despite its uniform visual appearance at the end of winter, the SAR data demonstrate the complex, heterogeneous nature of the ice cover laid down during formation and early growth.

RADAR BACKSCATTER MODELLING

To substantiate the conclusions drawn from the interpretation of SAR imagery and ground observations, the radar backscatter has been modelled based on an Integral Equation Model for surface scattering and an Independent Rayleigh Scattering Model for volume scattering [4]. The dielectric constant (4 discrete layers) is derived for a brine volume fraction given by the sea-ice model (Fig. 3), interpolating on empirical data [5]. Surface roughnesses are based on data for smooth, level first-year ice [6], while the size of scatterers (gas and brine inclusions) is derived from own field observations and data compilations [6].

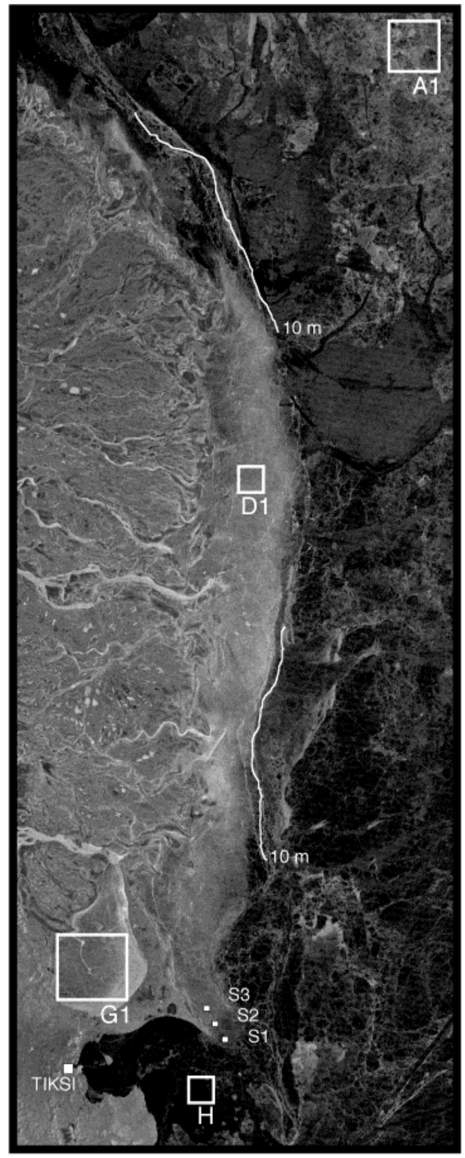

Fig. 2: SAR scene of eastern Lena Delta for March 5, 1997 (© Canadian Space Agency, scene roughly 85 km wide, non-linear scaling of backscatter values, incidence angle 45-50˚).

The backscatter model indicates a reduction in σ^o by roughly 5 dB for ice grown from water of salinity 0.5 to 10 ‰ (Fig. 4). This is attributed mostly to the decrease in penetration depth with increasing brine volume, reducing the volume-scattering contribution from gas and brine inclusions in the lower ice layers. Simulations for different pore diameters in winter sea ice demonstrate the strong impact of scatterer size on σ^o, which varies by roughly 12 dB for spherical pores with diameters ranging between 1 and 2.5 mm at incidence angles of 40 to 50˚. These contrasts are diminished as the ice warms in spring. A number of

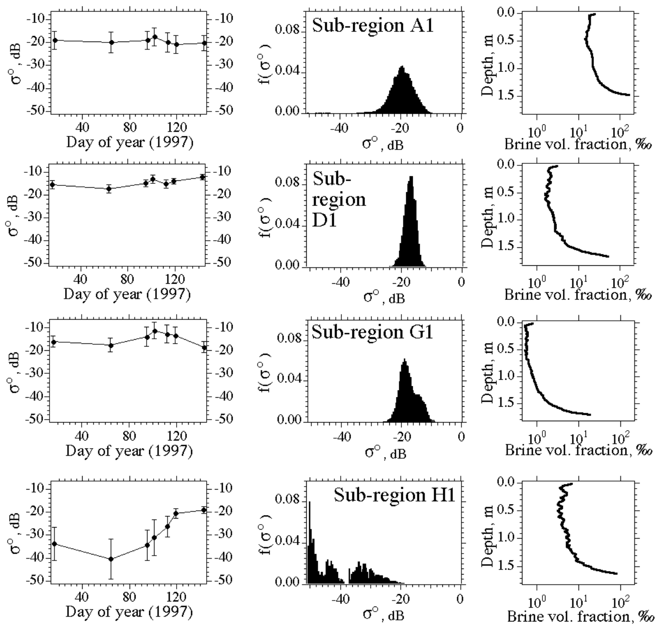

Fig. 3: Time series (left) and frequency distributions (center, March 5, 1997) of backscatter coefficients and ice brine-volume fractions from model simulations for March 5, 1997.

uncertainties and the lack of comprehensive data sets to better constrain the simulation of the ice-air and ice-water interface pose limits to the interpretation of model results. This also affects the simulation of the evolution of σ^o during spring and early summer, with surface scattering less affected by changes in ice temperature and salinity than changes in surface roughness due to ablation processes. In summary, the results support the conclusions from the previous Section and indicate a distinct reduction in σ^o as the surface water salinity increases above 2 to 5 ‰ (corresponding to ice salinities of 0.4 to 0.9 ‰). It needs to be investigated, how changes in the morphology and density of gas inclusions, which also strongly depend on the bulk ice salinity, may amplify such backscatter contrasts.

The observed reduction of σ^o for grounded low-salinity ice in the coastal regions is most likely attributable to changes in the character of liquid and gas inclusions of the lowermost ice as it freezes to the bottom.

CONCLUSIONS

SAR imagery revealed a distinct zonation in backscatter characteristics of the ice cover off the eastern Lena Delta in the Laptev Sea. Field studies and backscatter modelling indicate that a prominent transition between coastal, high-backscatter ice and offshore sea ice with lower-mean and

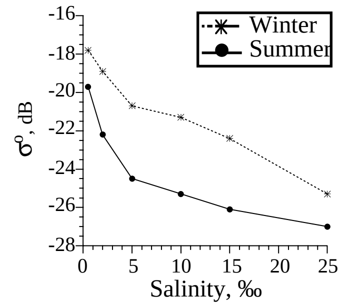

Fig. 4: Backscatter coefficients as a function of surface water salinity from which ice was grown. C-band with incidence angle 50°, air bubble radius 2 mm, brine inclusion radius in deeper layers 0.35 mm (contribution in upper layers neglected due to small volumes).

higher-variance backscatter coefficients are the result of gradients in ice dielectric properties, possibly aided by associated changes in pore morphology. Ice-growth simulations furthermore show that large radar penetration depths in the low-salinity nearshore ice allow for detection and mapping of bottom-fast ice and its evolution during the course of winter. These results indicate that time series of SAR data may aid in the study of key processes associated with river discharge and land-ocean interaction in Arctic shelf environments.

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