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Geophysical and atmospheric controls on Ku-, X- and C-band backscatter evolution from a saline snow cover on first-year sea ice from late-winter to pre-early melt

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ABSTRACT

This study investigates changes in Ku-, X- and C-band microwave backscatter, co-polarized ratio and dual-frequency ratios, to changes in *in-situ* measured snow thermophysical properties, driven by surface radiation measurements, during a 7-day transition from late winter to pre-early melt on a highly saline snow cover on smooth first-year ice. A surface-based Ku-, X- and C-band microwave scatterometer system is used near coincident with *in-situ* thermophysical snow measurements. A frequency-dependent penetration depth model is utilized to simulate diverse variations in Ku-, X- and C-band penetration during fluctuating snow thermophysical and atmospheric conditions. These results helped improve the interpretation of observed changes in Ku-, X- and C-band backscatter. Overall, dielectric loss associated with presence of brine throughout the snow volume, is observed to be the governing factor affecting microwave penetration. Our results indicate significant differences in observed microwave backscatter and derived co-polarized ratio and dual-frequency ratios, for all three frequencies during the transition from cold late winter phase to warm pre-early melt onset phase. C-band demonstrates the greatest increase in backscatter and co-pol ratios, followed by X- and Ku-bands. The dual-frequency ratio combinations clearly demonstrate their ability to separate sensitivities in frequencies by characterizing changes in backscatter during the 7-day transition. Our results indicate strong direct influence of downwelling shortwave and longwave radiation on snow brine volume and dielectric properties, which drives changes to Ku-, X- and C-band microwave backscatter and its associated co-polarized ratio and dual-frequency ratios. Our results demonstrate the ability of an observational multi-frequency active microwave approach to illustrate frequency-, polarization- and incidence angle-dependent changes in microwave backscatter from snow covers on first-year ice, at varying atmospheric and snow thermophysical conditions.

1. Introduction and background

The Arctic has demonstrated dramatic reduction in sea ice cover and its extent over the past few decades, manifested by extensive loss of old, multi-year ice (MYI) Comiso,2012 replaced by thinner, younger first-year ice (FYI) (Maslanik et al., 2011), with accompanying decline in spring snow depth (Stroeve et al., 2014; Webster et al., 2014). Snow cover on FYI exhibits diverse accumulation and redistribution rates and its electro-thermophysical properties demonstrates high spatiotemporal variability from hourly to seasonal time scales (Iacozza and Barber, 2010). Recent decline in the spring snow depth and change in precipitation pattern from snow accumulation to rain-on-snow events has influenced recent thinning of sea ice and increased the proportion of bare sea ice, which has a lower albedo than snow covered sea ice (Perovich and Polashenski, 2012). With amplified water vapor and thermodynamic gradients between the ocean and the atmosphere due to fluctuating atmospheric circulation patterns (Kapsch et al., 2016), snow cover in a warming Arctic are more likely to become thinner and more saline (Blanchard-Wrigglesworth et al., 2015). Moreover, delayed sea ice freeze-up may lead to thinner FYI and earlier melt-onset (Stroeve et al., 2014), reducing time for snow accumulation on FYI.

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Altogether, snow cover plays a crucial role in modulating sea ice ablation and accretion processes (Curry et al., 1995), altering and influencing polar atmospheric and oceanic circulation patterns (Deser et al., 2000).

Active microwave remote sensing has a demonstrated capacity to illustrate the thermophysical and electrical state of snow covered FYI (Barber and Nghiem, 1999; Yackel and Barber, 2007), where snow thermophysical properties influences microwave interactions through propagation and scattering within the snow/sea ice system, including snow salinity, density, temperature and grain size (Barber et al., 1998; Fuller et al., 2015; Fuller et al., 2014; Nandan et al., 2016; Scharien et al., 2010). During freeze-up and early winter seasons, in homogeneous dry (cold) snow conditions (with nearly zero downwelling shortwave radiation), microwaves achieves near-complete penetration through the snow cover with negligible attenuation, although brine at the snow/sea ice interface contributes to primary microwave scattering and attenuation, depending on the frequency employed (Barber et al., 1998; Nghiem et al., 1995). Elevated brine concentrations at the snow/sea ice interface and in the basal snow layers has been associated to strong upward brine-wicking by the overlying snow cover due to capillary action, from the underlying sea ice surface, during freeze-up; and/or also due to the snow covers overlaying highly saline frost flowers growing on thin ice (Barber et al., 1995; Drinkwater and Crocker, 1988). However, during the transition from late-winter to early melt season, more complexity in microwave interaction from within the snow volume is observed due to snow pack metamorphism (rapid kinetic snow grain growth throughout the snow pack), modifications in snow temperatures and subsequent increase in high dielectric basal snow layer brine volumes. Additionally, the electrical properties during this transition period are also controlled by the presence of moisture in the snow cover, driven by atmospheric forcing including diurnal oscillations in air temperature (due to varying downwelling/upwelling longwave radiation, and downwelling/reflected shortwave) (Barber and LeDrew, 1994; Barber and Nghiem, 1999; Hanesiak et al., 1999), persistent cloud cover (Barber and Thomas, 1998) and occasional precipitation such as rain (Fuller et al., 2014). Changes in brine volume at/or near the snow/sea ice interface and/or presence of moisture on the surface/within the snow cover (especially during pre-melt onset) changes the thermophysical, dielectric and scattering properties of the snow cover (Barber and Nghiem, 1999; Drinkwater and Crocker, 1988), leading to increased attenuation of microwave energy. This in turn may conceal relatively small thermophysical variations such as snow salinity and temperature in the snow basal layers, which is essential to quantify active microwave derived snow thickness estimates on FYI.

Recent studies using C-band reveal complex microwave scattering within the snow cover, restricting the C-band microwaves to retrieve snow thickness on Arctic FYI, owing to the presence of a high salinity snow layer, with higher than expected quantities of salinity concentrations in the top most layers of the snow cover (Fuller et al., 2014; Gill et al., 2015; Komarov et al., 2015). Previous studies of snow covered FYI have used a single-frequency approach (Barber and Nghiem, 1999; Barber and Thomas, 1998; Fuller et al., 2014; Hanesiak et al., 1999; Scharien et al., 2012) using C-band SAR and scatterometer observations, linking atmospherically driven changes in snow-covered FYI electric and thermophysical properties to C-band microwave backscatter. Use of multi-frequency microwave approaches on sea ice related studies (Dierking, 2010; Jezek et al., 1998; Livingstone et al., 1987; Nandan et al., 2016) have recommended its utility to characterize the snow geophysical and thermodynamic state on FYI. Moreover, temporal variations (*i.e.* hourly to weekly) in multi-frequency microwave backscatter are poorly understood, owing to dynamic snow thermophysical changes and related atmosphere-snow/sea ice interactions at the high-resolution *in-situ* or *plot-scale*. Plot-scale studies are essential for understanding the intricate '*detailed*' spatiotemporal behavior of various thermophysical properties and processes controlling the microwave backscatter at different frequencies.

Currently operational synthetic aperture radar (SAR) sensors (*e.g.*, COSMO-SkyMed, TerraSAR-X, RADARSAT-2 and LOS-2/PALSAR-2) operate over a wide range of frequencies, polarizations, spatial resolutions (1–1000 m), revisit times and at swath widths of 30–500 km. However, these SAR sensors also potentially introduce intrinsic sampling ambiguity, adding significant uncertainty to direct snow/sea ice thermophysical interpretation (Geldsetzer et al., 2007); due to presence of possible spatial heterogeneity of snow cover types on FYI, within a single SAR resolution cell. Moreover, SAR signals acquired from these above-mentioned sensors may be temporally de-correlated, owing to the dynamic temporal variability of snow/sea ice thermophysical properties. Therefore, it is currently difficult to implement multi-frequency satellite datasets on a high-resolution plot-scale snow covered FYI scenario. To avoid these issues, unambiguous *in-situ* measurements of snow/sea ice thermophysical properties, coincident to homogeneous high spatial and temporal resolution *in-situ* microwave backscatter measurements is recommended (Geldsetzer et al., 2007). Though a significant amount of research has evaluated sensitivities of different microwave frequencies to snow thermophysical properties using surface-based and airborne multi-frequency and multi-polarization active microwave measurements (Onstott, 1992; Onstott et al., 1979; Livingstone et al., 1987; Lytle et al., 1993; Beaven et al., 1995; Nandan et al., 2016;), no studies have been conducted using a time-series of multi-frequency microwave observations nearly-coincident with *in-situ* snow/sea ice thermophysical property and meteorological measurements, from a saline snow cover on FYI.

This study presents time-series of surface-based microwave backscatter measurements acquired at Ku- (17.25 GHz), X- (9.65 GHz) and C-band (5.52 GHz) frequencies, to examine the thermophysical and atmospheric controls on microwave backscatter from a 16 cm highly saline snow cover on smooth FYI, during the transition phase from late winter to the pre-early melt onset season. These frequencies are examined because they match closely to the center frequencies of recent, currently operating and imminent space-borne scatterometer and SAR systems (*i.e.* OSCAT, RISAT, ASCAT, QuikSCAT, TerraSAR-X, COSMO-SkyMed, RADARSAT-2, Radarsat Constellation Mission and Sentinel-1A/B). Utilizing *in-situ* measured co-polarized (σ^0_{VV} and σ^0_{HH}) microwave backscatter measurements, this study employs an experimental approach to understand the sensitivity of Ku-, X- and C-band microwave backscatter to an atmospherically forced and warming saline snow cover. σ^0 is the conventional normalized measure of radar cross section per unit area called *"sigma nought"*, while VV or HH represents co-polarized backscatter in vertical and horizontal polarizations respectively. In addition to σ^0_{VV}, σ^0_{HH} and the co-polarized ratio (γ_{co}), we introduce dual-frequency ratios (γ_{DFR}) as a new parameter to investigate its utility for sea ice related studies. All these parameters are then used to quantify the influence of atmospheric forcing on snow thermophysical and dielectric properties, influencing microwave snow interactions at all three frequencies. To help achieve our research objectives within the study context, we address the following questions:

1) What are the differences in Ku-, X- and C-band σ^0_{VV}, σ^0_{HH}, γ_{co} and γ_{DFR} for different/changing snow on FYI thermophysical property and atmospheric forcing scenarios?
2) How do air temperature (T_a), incident shortwave ($K_\downarrow$), incident longwave radiation ($L_\downarrow$), snow temperature (T_S) and snow brine volume (φ_{bs}) affect the electrical properties of a saline snow cover on FYI?
3) Which are the dominant atmospheric forcing parameters affecting snow thermophysical properties, which in turn influences Ku-, X- and C-band σ^0_{VV} and σ^0_{HH} from the snow covered FYI?

2. Methods

2.1. Study area

The Ku-, X- and C-band time-series microwave backscatter acquisitions and near-coincident *in-situ* snow thermophysical property