DIURNAL CHANGE FROM SURFACE TO VOLUME SCATTERING INDUCED BY THAW AND REFREEZE OF THE THE SNOW COVER: A THERMODYNAMIC APPROACH.

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1. INTRODUCTION

Sea ice morphological features are of major relevance to oceanic and general circulation models as well as navigation or oil and gas exploration [1]. Beside their first order impact on drag coefficients [2], they create a horizontal heterogeneity of the dynamic and therefore thermodynamic conditions at the ice water interface which control ocean-ice-atmosphere fluxes. However, computer limitations preventing the resolution of boundary layer processes with two roughness scales and unavailability of adequate data sets regarding the roughness variability and more specifically ridge distribution [3] [4] over an ice field prevent the integration of these properties of the sea ice cover into large scale models.

Synphetic Aperture Radars (SAR) with improved resolutions, up to 3 meters in the ultra-fine-mode of RADARSAT-2, and the independence of microwaves from cloudy conditions often encountered in polar areas, offer the potential tools to better describe the statistics of large roughness features at scales compatible with large scale models [5] [6] [7]. Whereas most morphological features are satisfactorily extracted from images throughout the winter season, the contrast between the ridge network and the un-deformed sea ice sheet is at its maximum during the melt season. At spring, the increase of the water content in the snow makes it opaque to microwaves and, in turn, causes surface scattering to be the main contribution of radar images. As a consequence, the radar signal becomes mainly function of the surface small scale roughness and interface slope. The angular dependence of surface scattering creates conditions allowing a higher return from ice blocks with a surface oriented perpendicularly to the SAR incident beam and on the contrary a reduced backscattering from other areas within the scene where forward scattering causes the beam energy to be scattered away from the antenna.

2. DIURNAL VARIABILITY

As a result of the dependence of microwaves on the dielectric properties of the material they interfere with, the microwave signature of sea ice changes dramatically with the season. While pure ice and dry snow do not cause significant scattering due to dielectric properties which do not differ much from the air, liquid water acts as an efficient absorber reducing accordingly the intensity of the microwaves backscattered toward the satellite [8]. The availability of liquid water in the snow is the result of a shift in the thermodynamic balance of the snow and sea ice covers. During winter, the atmosphere pumps heat out of the ocean through a negative temperature gradient across the ice and snow media. The heat balance is then negative and requires latent heat of freezing to be released at the ocean-ice interface to maintain equilibrium. The ice sheet grows. At spring, with the irradiance and air temperature increasing, the heat fluxes are reversed with the ice and snow media becoming the heat sinks. Quickly the snow becomes isothermal and melt starts to absorb the excess heat as latent heat of fusion. During this period, the snow layer is a tri-phasic medium in which water changes state to balance radiations (short and long waves) and conductive heat fluxes variations. As a consequence, the surface layer of the snow cover is subject to a diurnal cycle of thaw during day time and refreeze at night which translates into a parallel diurnal cycle on snow wetness content. In addition, as the atmosphere plays the role of heat source and sink over this cycle, it is expected that the larger wetness fluctuations are to take place closer to the surface with decreasing impact as we get deeper into the snow cover.

This cycle is of major relevance to microwave remote sensing applications and specifically to pressure ridge extraction [9] [10]. With wetness decreasing overnight, more energy can penetrate the snow medium, enhance the volume scattering contribution and hide details of the scene better revealed through surface scattering. In the following, we present a simulations of the thermodynamic adaptation of isothermal snow layers of different thickness subjected to a diurnal fluctuation of the radiative forcing and discuss the results in relation to snow water content profiles and snow surface wetness observations collected offshore of Kuujjuarapik, Hudson Bay, Canada.

3. THE SIMULATION

At spring solar radiation triggers melt, first at the very surface of the snow cover. Then, as heat is conducted downward and the increased radiation absorbed within the snow cover adds up, the snow temperature rises up to the freezing point causing melt and the metamorphosis of the snow. The increased wetness subsequently reduces surface albedo, in turn increasing solar radiation absorption [12]. Our model computes the melt output and refreeze of an isothermal snow layer during a 24 hour period. Thin snow cover conditions characteristic of the snow layer observed on pressure ridge ice blocks are simulated.

The energy balance forced by incoming $L^{\downarrow}$ and outgoing $L^{\uparrow}$ long-wave radiation, incident $S^{\downarrow}$ and reflected $S^{\uparrow}$ short-wave radiation and turbulent atmospheric heat flux Q_{atm} was computed as a function of the snow surface orientation:

$$Q_{melt/freeze}(\Theta,\Omega) = L^{\downarrow} + S^{\downarrow} - L^{\uparrow} - S^{\uparrow} + Q_{atm}$$

Θ and Ω are the angles between the normal to the snow surface and respectively the south-north and east-west axes. The snow is considered isothermal and conductive heat fluxes neglected in all the domain with the exception of the snow-ice interface. At the ice snow interface a downward heat flux Q_{ice} is imposed setting a linear temperature gradient across the sea-ice, and temperatures at the freezing point on both sides. In freely draining snow, water is held by capillary attraction in between snow grains. With snow metamorphosis, snow grain growth causes a reduction of the sites of contact in between ice crystals which reduces the water retention capacity of the snow [13]. In order to implement free drainage an arbitrary maximum wetness was set for the simulated snow conditions.

4. RESULTS AND DISCUSSION

For a snow thickness superior to 2 cm, we observe during the day an increase of the wetness content throughout the snow cover with a maximum in the top layers. As the day goes by, drainage from the top layers causes an increase in the wetness of the lower cells. As expected, the absorption of the incident radiation causes a decrease in the incoming radiative heat flux with the depth. Below 2 cm thickness, the drainage causes saturation of the snow at the ice-water interface. At this point the simulations were interrupted considering that once saturated the bottom layer would be the site of transverse drainage causing some water to be exported on the sides of ice blocks which could not be simulated through our model.

While snow surface orientations causes a slightly higher melt rate when the total surface irradiation throughout the day is higher, the main difference was observed in the top cell of the domain. In this area the snow surface is the site of intense melt when incident short wave radiations are at their maximum. This is coherent with field observations which revealed the development of a wet film on snow feature surfaces favorably oriented. This brings some reflection with regard to microwave remote sensing. It suggests that forward scattering could be enhanced on parts of the snow field when the geometry of the sun and radar incident beams are such that surfaces coated with a wet film constitute a large part of the scene. Although SAR is not dependent on sun radiations, the sun irradiation of the various surfaces of a deformed ice field could be of relevance.

At night, our simulation show a refreeze at the snow air interface which slowly pumps heat out of the top layers of the snow cover. Within the snow cover, we observe that freezing can be slightly enhanced or reduced depending on the long wave radiation forcing. As expected, the heat flux through the sea-ice causes significant freezing in the lower cells of the domain. This is coherent with observations from Nicolaus et.al. who observed a superimposed ice formation on top of the saline sea-ice [14]. On thin ice, refreezing can be complete or leave a thin layer of saturated snow trapped in between a frozen top layer and the ice itself. This results from the heat conduction in the ice which is too low to extract the latent heat accumulated during the day. However, without an accurate modeling of transverse drainage, the thickness of the saturated layer remains too uncertain to give much credit to this conclusion. Nonetheless, refreezing of the surface layer and the reduction of the water content in the top layer of the snow suggest an increased volume scattering component on morning images compared to mid-day images.

5. REFERENCES

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