Remote Sensing of Sea Ice Surface Thermal States under Cloud Cover

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Abstract – It is necessary to know sea ice surface thermal states under cloud cover to evaluate cloud effects in the overall climatic feedback mechanisms in polar regions. The challenge is that traditional methods using radiometers such as AVHRR for surface temperature measurements fail under cloudy conditions. We present a new method combining C-band radar data to study sea ice surface temperature change and visible/infrared radiometer data to identify clouds. From laboratory experiments, we show that C-band radar backscatter is sensitive to sea ice surface thermal states. This relationship is utilized to develop the methodology for the sea ice surface temperature study. We present an example with ERS-1 SAR data, AVHRR data, and field experiment measurements over first-year and multi-year sea ice in the Canadian Arctic Archipelago to illustrate the methodoly. In this example, SAR data show an increase in sea ice surface temperature, caused by an excess in the surface heat balance under cloud cover. The method is applicable to Arctic sea ice containing a sufficient amount of salinity such as first-year ice. For Antarctic sea ice, this method is particularly appropriate since the Antarctic ice cover consists of vast regions of first-year ice and also the salinity level is higher compared to that contained in Arctic sea ice of similar age and structure.

INTRODUCTION

Changes in sea ice surface thermal states modify surface albedo, which induces further changes in surface heat balance and subsequent changes in ice surface temperature. An amplification effect in the ice-albedo feedback process has been recognized [1] and various simulations of global warming have indicated the importance the ice-albedo feedback [2] [3] [4]. In the feedback process, cloud cover interferes with the distribution of shortwave and longwave radiations, and thus strongly affects the surface energy balance [5] [6] [7]. Yet it is currently uncertain whether the net cloud feedback is positive or negative because of the complexity of polar cloud feedback mechanisms in the atmosphere-ice-ocean system [8]. To determine the overall effects, it is necessary to know sea ice thermal states under both cloud covered and cloud free conditions. The challenge is that traditional methods using radiometers such as AVHRR for surface temperature measurements fail under cloudy conditions. Spaceborne imaging C-band radars such as the operational ERS and RADARSAT SARs or the future ENVISAT SAR has the capability to see through clouds and probe near-surface conditions of sea ice over large areas. The question is whether radar backscatter signature from sea ice is related or sensitive to surface thermal states. We conducted controlled experiments to investigate the relationship between C-band radar signatures and sea ice thermal conditions. We also present an example using ERS-1 data, AVHRR data, and field measurements over first-year and multi-year sea ice.

BACKSCATTER AND SURFACE TEMPERATURE

To study the sensitivity of C-band backscatter to sea ice surface temperature, we conducted sea ice experiments the Geophysical Research Facility (GRF) at the Cold Regions Research and Engineering Laboratory (CRREL). The sea ice sheet was grown in the GRF pool fill with water of $30^0/_{00}$ salinity by a salt mixture typically of natural sea water. A polarimetric C-band scatterometer was used to take radar data at different incident angles and polarizations.

We obtained time-series measurements of sea ice backscatter, temperature, salinity, and other physical

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parameters over several diurnal thermal cycles. The experiments included two distinct thermal regimes for ice surface temperatures above and below the mirabilite ($Na_2SO_4 \cdot 10H_2O$) crystallization point (−8.2°C). We take advantage of the diurnal radiation variations (see Fig. 1a) to drive the surface temperature of the ice sheet (see Fig. 1b).

The temperature started to increase at the beginning of the insolation and increased sharply along with the short-wave radiations. The slope of the temperature curve breaks at about 10 am corresponding to the cloud overcast time. The temperature continued to rise with a slowlier rates during the late morning and early afternoon hours when the insolation loss was compensated by a high level of long-wave radiations under the cloud cover. Then, the ice surface cooled down in the evening. The short period of local warming before midnight is also observed in the temperature curve. During the early hour of 20 February, the temperature steadily decreased with decreasing long-wave radiations.

Fig. 1c and 1d shows backscatter at both horizontal (σ_{hh}) and vertical (σ_{vv}) over a full day cycle. Backscatter change at different incident angles and polarizations follows exactly the same trend as the temperature variations. In this case, sea ice surface temperature are all above the mirabilite point. In another experiment with the ice sheet grown from the same sea water, backscatter data were obtained over 2 diurnal cycles with sea ice surface temperature below the mirabilite point.

From these experiments, the results show that (1) backscatter is very sensitive (5-10 dB change) to ice surface temperature change, (2) the correlation between backscatter and temperature is positive, (3) the temperature cycling effects are reversible, and (4) the backscatter change is stronger over the higher temperature regime. The study indicates that the eutectic phase distribution and corresponding geometric variations of brine pockets are responsible for the observed backscatter signature of the thermal variations.

FIELD EXPERIMENT OBSERVATIONS

We obtain ERS-1 SAR data acquired at a local nighttime and AVHRR data on 6 May and 9 May 1993 over the SIMSS (Seasonal Sea Ice Monitoring and Modeling Site) experiment area. SIMMS is a Canadian long-term field experiment program and the sea ice area is located between the Griffith Island and the Cornwallis Island in the Canadian Arctic Archipelago.

Field measurements show that this sea ice area consists of multi-year ice floes and first-year ice grown at different consolidation periods. AVHRR and field data indicate a clear sky on 6 May and stratocumulus cloud cover on 9 May. We coregister the SAR data on the 2 dates and process the images to derive the image of $\Delta = \sigma_0(9 \text{ May}) - \sigma_0(6 \text{ May})$. The results show that the cloud cover at nighttime has a 'blanket effect' that increases sea ice surface temperature corresponding to the backscatter increase. The blanket effect is due to cloud cover keeping long-wave radiation from loosing to the outer space and consequently raises sea ice surface temperature. This is consistent with an increase of more than 30 $W \cdot m^2$ in the all-wave net radiation measured in situ.

The increase in ERS backscatter is observed with increasing ice surface temperature for first-year and younger ice but not for perennial ice. This is because a sufficient amount of salinity in sea ice is necessary for observable thermal effects on backscatter. Thus, the observation method using spaceborne C-band SAR is applicable to first-year sea ice. For Antarctic sea ice, this is particularly appropriate for remote sensing of sea ice thermal states because of vast first-year sea ice areas in the Antarctic ice cover and because of the high salinity level compared to that contained in Arctic sea ice of similar age and structure. Combined with AVHRR imagery for cloud detections, radar signature from spaceborne SAR provides the basis to determine net effects of the cloud-ice-albedo feedback processes in the atmosphere-ice-ocean system.

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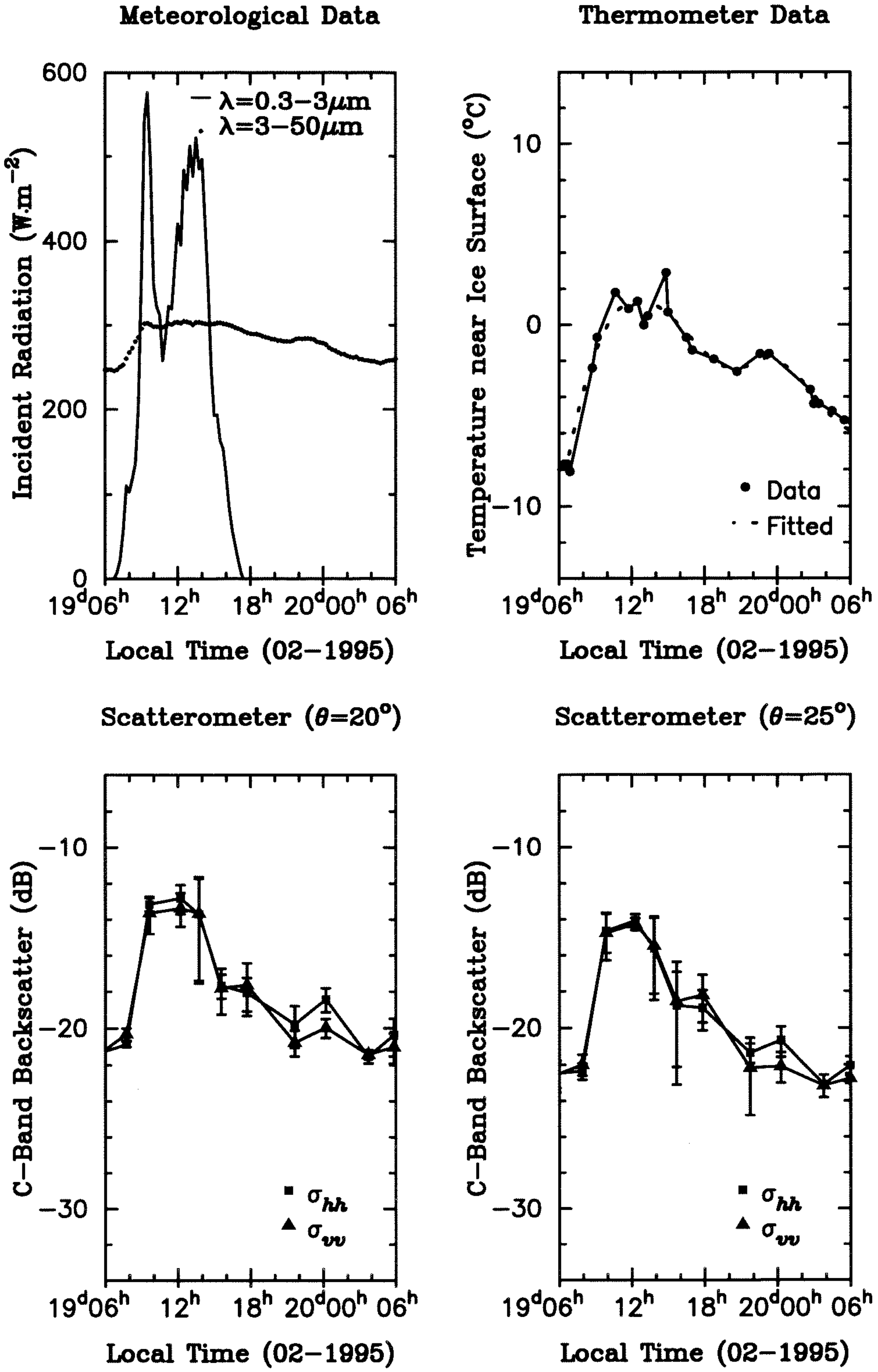

Figure 1. Eperimental results: (a) Incident shortwave and longwave radiations, (b) temperature measured within 1 cm above the sea ice surface, (c) C-band backscatter data at 20° incident angle, and (d) C-band backscatter data at 25° incident angle.