1.5 MONITORING THE SEASONAL DECAY OF FIRST YEAR SEA ICE AT THE CANADIAN ICE SERVICE WITH NOAA AVHRR

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1.0 INTRODUCTION

The Canadian Ice Service (CIS), a branch of the Meteorological Service of Canada (MSC), is mandated to continually monitor ice conditions in Canadian coastal areas in order to support ship navigation and other marine activities in waters where ice is present. Interpreting satellite image data is at the core of this monitoring task – NOAA AVHRR and RADARSAT-1 being the Service's primary data sources. The CIS receives and processes Local Area Coverage (LAC) Advanced Very High-Resolution Radiometer (AVHRR) (Kidwell, 1991) data several times daily. Although cloud cover limits the use of these data, clear sky data are routinely used to complement RADARSAT-1 coverage. The spring and summer melt of first year ice and the associated reduction in ice strength is a major determinant in the timing of Arctic marine activities in ice-covered waters. As such, the development of techniques whereby the state of Arctic first year sea ice melt can be reliably monitored with AVHRR and RADARSAT-1 is a high priority at the CIS.

This paper investigates the utility of AVHRR channel 1 and channel 2 data (hereafter AVHRR 1 and AVHRR 2 respectively) in the operational monitoring of the seasonal melt of Arctic first year ice. The sea ice volume's optical and thermal properties are modified significantly by melt-related physical changes. As a result, the appearance of first year sea ice in AVHRR data begins to change with the onset of melt conditions in the Arctic (De Abreu, 1996). This fact holds some promise for extracting information regarding the state of sea ice melt from these data.

2.0 STAGES OF FIRST YEAR SEA ICE MELT

The CIS is focusing on the following five stages of melt distilled from those proposed by Barber *et.al* (2001) : *Winter Ice, Snow Melt, Ponded Ice, Drained Ice and Rotten Ice.* The Winter Ice Stage is not a melt stage, but is useful as a baseline for detecting the onset of the melt process. During the Snow Melt Stage, liquid water content in the overlying snow volume steadily increases, snow grains increase in size and the snow volume may decrease in depth. Importantly, the strength of the ice volume begins its seasonal decline as the volume begins to warm and brine volumes increase. In a spatial sense, the icescape is still relatively homogeneous. The Ponded Ice stage is characterized by the appearance of melt ponds and the transformation of the surface into a heterogeneous mix of surface water and interstitial wet snow areas. The primary source of the melt water is the snow cover. The subsequent Drained Ice stage describes the drainage of surface water from both snow melt ponds and melted ice back to the ocean. The primary drainage paths are laterally into cracks and holes and vertically through the snow/ice volume. During the Ponded and Drained Ice Stages, the mechanical strength of the ice volume decreases dramatically (Johnston *et.al.,* 2001). As such, the detection of the onset of these two melt stages is critical from an operational perspective. The final stage, Rotten Ice, is characterized by a heterogeneous mix of open water and severely decayed ice dotted by saline melt ponds and thaw holes.

3.0 DATA AND METHODS

In order to support CIS operational analysis, AVHRR data are converted to an 8 bit product and registered to a standard projection for display and analysis. The 8 bit digital numbers (DNs) essentially represent raw counts of the reflected top of atmosphere (TOA) radiance. The data is not calibrated and the visible channels are not normalized to account for solar zenith angle dependence and/or anisotropic effects of the surface or intervening atmosphere. In order to facilitate temporal monitoring of melt conditions with these data, it is necessary to normalize these datasets. Towards this, the NOAA 14 data examined here were calibrated and nominally converted to TOA reflectance (Kidwell, 1991). In order to minimize the effects of scene anistropy, datasets were restricted to a specific sun-

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scene-satellite geometry. Clear sky AVHRR scenes were identified manually by examining all five channels for cloud contamination and by utilizing surface-based cloud observations.

4.0 IDENTIFICATION OF ICE MELT STAGE

Operationally, the CIS requires the regular production of a chart which describes the stage of ice melt throughout the Canadian Arctic. This section assesses the potential of AVHRR data to accurately identify these melt stages. Figure 1 contains the average top-of-atmosphere reflectance calculated over a nine pixel subarea collected over the surface study area of the Collaborative Interdisciplinary Cryospheric Experiment 2000 (C-ICE '00) located in the central Canadian Arctic Archipelago (Figure 2). Of special interest is the seasonal transition of reflectance over this first-year ice study area and the possibility of identifying melt stages through the monitoring of AVHRR 1 and 2 reflectance values. Figure 2 contains subareas of AVHRR channel 1 data collected in the spring/summer of 2000.

Due to its higher sensitivity to changes in snow grain growth and increases in snow liquid water content (in the upper layers) (Warren, 1982), the departure from the Winter stage and the beginning of the Snow Melt period is first evident as a decrease in AVHRR 2 reflectance. From April 17 to June 14, AVHRR 2 reflectance decreased from 74% to 64%, while AVHRR 1 reflectance appeared to increase 2% (Figure1). However, as the snow volume thinned and a slush layer at the snow-ice interface appeared and grew, AVHRR 1 reflectance decreased to 67% by June 19, just prior to the appearance of melt ponds. The Snow Melt stage can also be identified by the increased difference between AVHRR 1 and 2 when compared to the Winter Stage. Operationally, this seasonal difference regularly manifests itself as a change in the colour of sea ice within a standard RGB colour display where AVHRR channels 1 and 2 are loaded.

Within the month of June, the transformation and removal of the highly reflective snow cover and the appearance of lower albedo melt ponds causes dramatic and distinctive changes in sea ice reflectance. In situ observations indicate that melt ponds first appeared at the C-ICE '00 site after June 19. During the Ponding stage, the relatively homogeneous sea ice surface was transformed into a heterogeneous mixture of light blue-coloured melt ponds and white interstitial snow/ice areas. As a result, AVHRR 1 and 2 reflectances decreased in magnitude and were more variable over the study area. The AVHRR 1 reflectance decreased due to the increasing coverage of dark melt pond areas at the expense of the brighter snow covered interstitial areas (Figure 2). AVHRR 2 is sensitive to the liquid pond surface and the surface characteristics of the interstitial areas. The wet pond surfaces and the large-grained interstitial snow/ice areas thus drive the AVHRR 2 reflectance. Between June 19 and June 21, AVHRR 1 and AVHRR 2 reflectance decreased from 67% to 50% and 47% to 29% respectively as the pond fraction increased from 0% to 45% (Figure 1). Unfortunately no clear-sky AVHRR data were available over the peak ponding period of June 22-24, but it is assumed that both AVHRR 1 and 2 reflectances continued to decrease as pond fraction increased.

In terms of sea ice field experiments, the Drainage stage has gone relatively unobserved. In C-ICE '00, an attempt was made to further the understanding of this melt stage by extending the field camp observations into early July and by returning later via a Coast Guard icebreaker. Surface melt water on sea ice begins to drain as soon as there is pathway to the underlying ocean. Spring first year ice is pocked with seal holes and cracks that efficiently drain surface melt water in the late Ponding stage and early Drainage stage. As the Drainage stage progresses, the enlarged brine pockets interconnect to form vertical drainage pathways that allow melt water to drain vertically through the ice. The immediate effect of drainage is a reduction in the fraction of the ice surface covered by surface water. The newly uncovered remnant ice surface is often crumbly, rough and dull white in colour.

In C-ICE '00, surface drainage was first observed on June 24 and resulted in a decrease in melt pond fraction. AVHRR 1 and 2 data indicated an increase in TOA reflectance from 29% (June 26) to 37% (June 29) (Figure 1), which is consistent with the decreasing melt pond fraction and the 'whitening' of the surface observed at the field site. The AVHRR dataset indicates another, larger increase in reflectance that begins after the first week in July. Both AVHRR 1 and 2 reflectances increased dramatically to at least 60% and 46% respectively, with this increase being observed throughout the region (Figure 2). Although field observations were not available during this period, it is possible that this rebound in reflectance was the result of the disappearance of surface water due to mass vertical drainage of the ice cover.

In 2000, observations in the last week of July from the Coast Guard icebreaker Louis St. Laurent coincided with what was estimated to be the beginning of the Rotten Ice stage. Arctic shipping and icebreaker support typically begins in this part of July when the ice is considered very weak. Ironically, this is the least understood stage from a remote sensing perspective -- likely due to the lack of dedicated field observations.

Ice in the Rotten Ice stage has lost much of its mass and strength. In 2000, numerous thaw holes were visible in the C-ICE '00 area, which could best be described as a mixture of deep, saline melt ponds and dry, non-saline raised hummock areas. AVHRR reflectances decreased from the Drainage Stage to Rotten Ice stage. This is consistent with the reappearance of melt ponds on the icescape, this time primarily saline in nature and at a lower areal coverage (visually estimated at 40%) than at the peak of the Ponding stage.

5.0 CONCLUSIONS

The seasonal decrease in AVHRR 1 and 2 reflectances is distinctive throughout the stages of first year ice melt and thus holds good potential in their mapping. Automatic classification of AVHRR 1 and 2 data into these stages will have to contend with cloud interference and will require the definition of reflectance thresholds for each stage. Future work will define these thresholds and investigate the use of channel AVHRR/3 3A to mask out clouds. A synergistic way to use AVHRR and microwave data (passive and active) to map the progression of these stages over first year sea ice is currently under development.

6.0 REFERENCES

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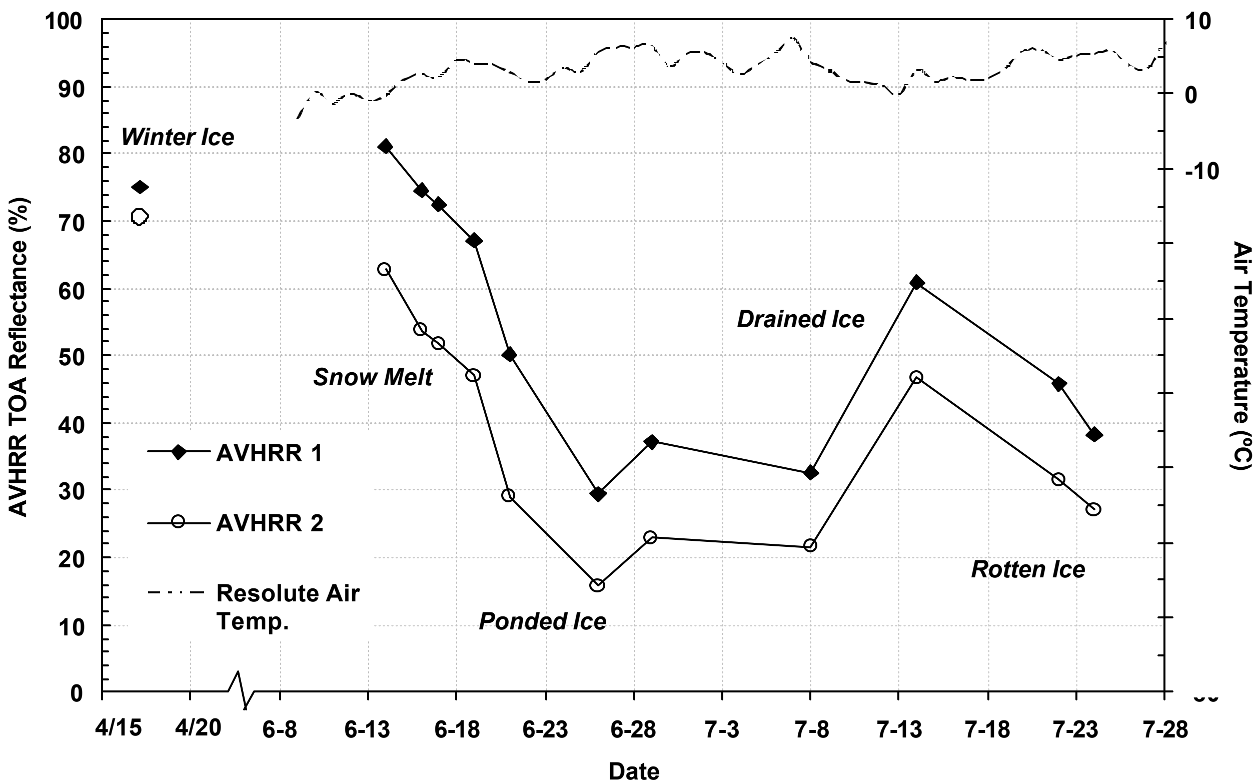

Figure 1. Seasonal variation in TOA AVHRR reflectance over fast first-year sea ice with Stages of Ice Melt, as determined by concurrent surface observations during C-ICE '00 . Air temperature measured at MSC weather station Resolute also shown.

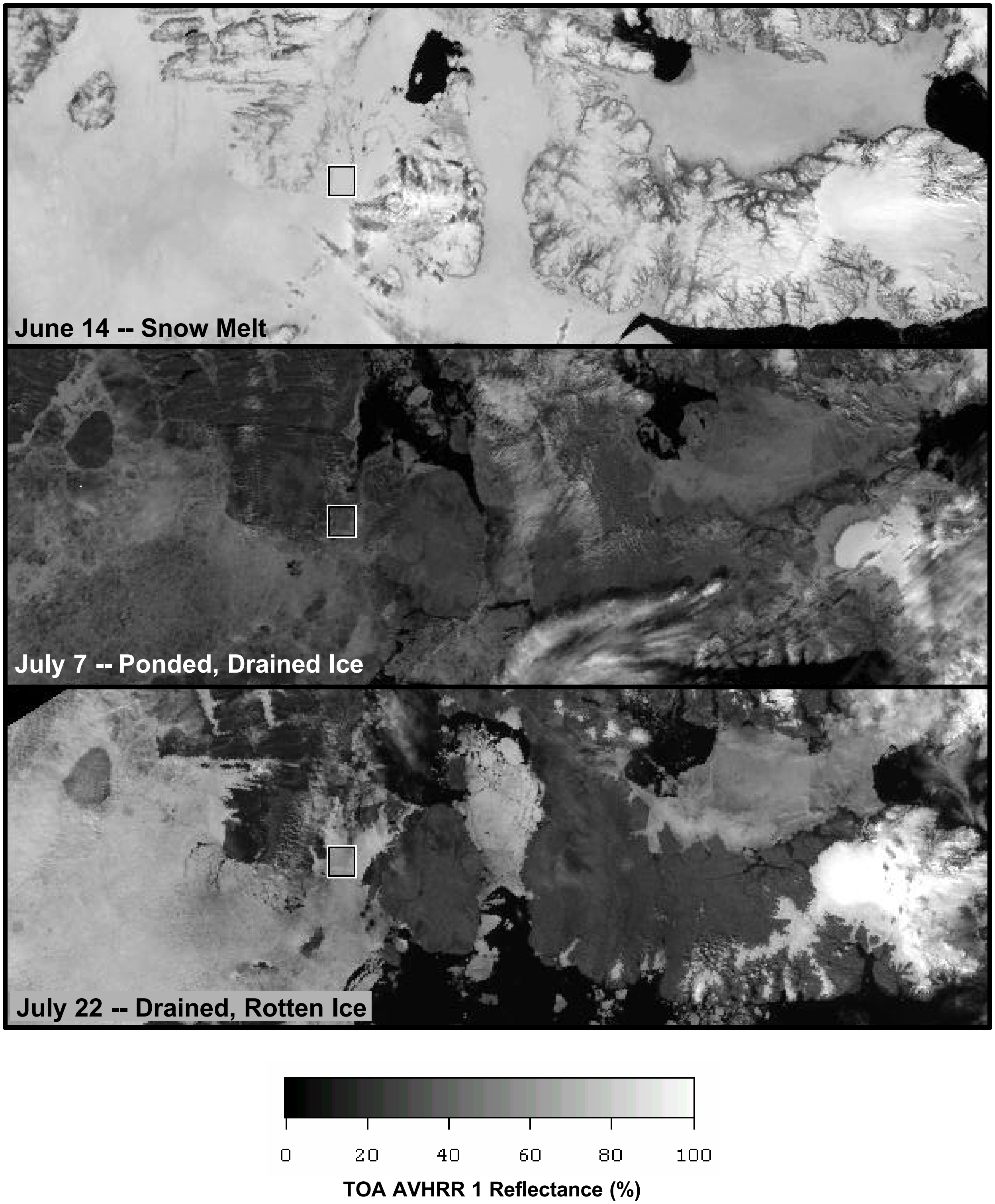

Figure 2. The transformation of TOA reflectance can be seen in these subareas of AVHRR 1 data collected during C-ICE '00 (location shown by inset box). The area is located in the Canadian Arctic Archipelago, specifically the waters off Barrow Strait and Lancaster Sound south of Devon Island, Cornwallis Island and Bathurst Island.