Abstract—Simulated sea ice was grown in an outdoor tank during the early winter seasons of 2001/2002 and 2005/2006. Microwave radiation was sampled every 5 min from the following three channels: 19, 37, and 85 GHz. Surface physical conditions were measured or observed to help in the interpretation of the radiometric behavior. This paper reports on results related to the following objectives: 1) linking the observed radiation to surface properties and processes; 2) classifying thin ice into emissivity-based surface types; and 3) assessing thin-ice parameter retrieval algorithms. This paper shows that ice of less than 4-cm thickness exhibits cycles of a sharp decrease of microwave emission caused by surface wetness followed by a gradual increase as the surface refreezes. This ice is particularly linked to meteorological conditions. Snow accumulation on relatively thick ice (> 20 cm) affects only the radiation from the 85-GHz channel. Thin-ice surfaces can be grouped into two radiometrically distinguished categories — the first includes slushy and wet surfaces and the second includes wet snow, dry snow, and dry bare-ice surfaces. Radiation from the second category is higher. The radiation from a refrozen slush surface appears to fall between these two categories. The variability of emissivity increases as the radiation frequency increases, particularly for the horizontal polarization channels. Existing algorithms of ice thickness, snow depth, and ice concentration were examined against the current data to study their sensitivity to variations of surface conditions. Limitations on their applications have been established.

Index Terms—Ice parameter retrieval, microwave emission from ice and snow, passive microwave, sea ice, thin ice.

I. INTRODUCTION

Thin ice is a complex material, as many physical processes are triggered by the sharp temperature gradient through its thickness. In addition, meteorological conditions during the early ice formation usually feature wet precipitation and sharp temporal variations of atmospheric temperature before the steady cold and dry winter conditions prevail. All these factors contribute to a complex surface from a physical and, hence, radiometric perspective and make the retrieval of surface parameters from microwave observations difficult. According to the World Meteorological Organization (WMO)’s ice-type nomenclature, thin ice includes all ice types less than 30 cm in thickness. However, the sensitivity of thin-ice surfaces to meteorological forces (atmospheric temperature and precipitation) is particularly pronounced for new ice (defined as ice of less than 10-cm thickness) where surface salinity is remarkably higher and spatially variable.

Several research programs were conducted in the last two decades to measure microwave radiation from snow-covered natural and artificial sea-ice surfaces in order to characterize the radiative behavior of the surface and, hence, improve methods of ice parameter retrieval. A most notable program was a series of laboratory experiments on thin ice conducted at the U.S. Cold Region Research and Engineering Laboratory in the early 1990s. It included measurements of microwave radiation under a wide range of surface and meteorological conditions [1], [2]. A main conclusion was that surface salinity, roughness, brine volume, and air-bubble size significantly affect the emission for microwave frequencies, while the effects of particulates and dissolved material were not too significant. In another study on laboratory and natural sea ice [3], an unexplained sharp rise in surface temperature was observed when the ice was between 1 and 2 cm in thickness, with a coincident decrease in the brightness temperature ($T_b$) at the 37 GHz channel ($T_{b_{37}}$). Most of the early studies on microwave properties of newly formed ice [4]–[7] focused on recording variations of $T_b$ with ice thickness or snow accumulation, in addition to the angular variation of the radiation. The effect of surface composition, which is triggered by weather events, was not a focus in those studies.

The first attempt in Canada to measure microwave radiation from artificially grown sea ice in an outdoor laboratory setting was conducted in the winter of 1998/1999 [8]. This was followed by two experiments in the winters of 2001/2002 and 2005/2006. Those experimental studies are known as ice-tank experiments. They were driven by a need to improve the retrieval of ice parameters (concentration and thickness) from passive microwave data in order to assist the Canadian sea-ice monitoring program. Surface-based radiometers were used to obtain a detailed record of the microwave brightness temperature of the ice surface at the following three frequencies: 19, 37, and 85 GHz at the same operational incidence angle (53°) of the passive microwave Special Sensor Microwave Imager (SSMI). Sampling started from the onset of freezing until the ice was roughly 25 cm thick. The outdoor setting, with full exposure to meteorological conditions (particularly to different forms of precipitation), made the ice conditions in the tank resemble natural ice to a large extent (except for the ice mobility).

Surface-based radiometer observations are a necessary step to understand the satellite observations. They guarantee the homogeneity of the footprints, and they are not affected by atmospheric influences, except for the reflected downwelling...
radiation. One purpose of this paper is to identify the impact of the complex conditions of a thin-ice surface on microwave emission in the absence of the equally complicated atmospheric influences. Estimates of ice concentration from different algorithms, for example, are known to be poor over thin ice due to its high spatial and temporal variabilities [9], [10]. The present measurements, with their negligible meteorological contamination, help to reveal where and why failure due to unfavorable surface conditions occurs. Whenever 85 GHz is mentioned, it refers to the SSM/I channel. However, the same observations and conclusions apply to the 89-GHz data from the more recent Advanced Microwave Scanning Radiometer.

II. EXPERIMENTAL SETUP

The ice tank is a circular above-ground swimming pool of 7.5-m diameter located at the National Research Council facility in Ottawa, Canada. It was filled with water of 28-parts-per-thousand (ppt) salinity and exposed to below freezing atmospheric temperature and precipitation. Results from two experiments were combined in the analysis presented in this paper. The first started on November 22, 2001, and ended on February 11, 2002, when the ice thickness reached 23 cm (with 8-cm snow depth), and the second started on November 23, 2005, and ended on January 10, 2006, when the ice thickness reached 24 cm (with 24 cm of snow and refrozen slush on the surface).

The Surface-Based Radiometer (SBR) system [11] was used to collect passive microwave data for this paper. The SBR system is a special-purpose data-acquisition platform designed solely for control and data acquisition using microwave radiometers. The radiometers are installed in weatherproof temperature-controlled enclosures allowing for better instrument stability. The system allows for a real-time graphical display of calibrated brightness temperature data.

For the 2001/2002 experiment, the radiometers used were manufactured by ATTEX Ltd. (Moscow) operating at 19-, 37-, and 85-GHz dual (H+V) polarization with 15° beamwidth horn antennas. These radiometers required frequent calibration during clear-sky conditions using the tipping method [12]. For the 2005/2006 experiment, the radiometers were replaced by new state-of-the-art radiometers manufactured by Radiometrics, Ltd. (Boulder, CO) operating at the same frequencies and dual polarization with 6° beamwidth horn antennas. These new radiometers are self-calibrating with a “quick-look” real-time accuracy of approximately 1 K.

Fig. 1 shows the tank filled with snow-covered ice. In the background are two radiometer housings; one samples the microwave radiation from the 19-GHz radiometer, while the other samples from the 37- and the 85-GHz radiometers. The position and pointing of the radiometers and data acquisition were controlled by a remote PC through specialized software (the SBR system). The system was housed in the trailer, shown in the background of Fig. 1. Calibration of the radiometers for the 2001/2002 experiment was performed once every few days under clear-sky conditions using cosmic radiation of the sky and a microwave absorber as calibration points (tipping curve technique). The footprint on the ice surface was approximately 1 m² from all channels.

III. RESULTS AND DISCUSSION

A. Evolution of Brightness Temperature With Variable Weather and Surface Conditions

Fig. 2 shows the evolution of brightness temperature in the vertical and horizontal polarizations from all channels during the first week of freezing (December 22–29, 2001). The labels on the horizontal axis are displayed in the format (ddd.hh:mm), where “ddd” is the day of the year, “hh” is the hour, and “mm” is the minute. On day 356 (December 22) and part of day 357, when ice was only a few millimeters thick, the brightness temperatures from the 19-GHz channel, which are \( T_{b_{19v}} \) and \( T_{b_{19h}} \), were significantly higher than the corresponding values from open water (typically 97 K and 150 K, respectively), although the penetration depth was higher than the ice thickness at this frequency. Those values agree with published data in [5]. The erratic behavior of \( T_{b} \) during the snow and freezing rain event (end of day 357 and beginning of day 358) was caused by the unsettled condition of freezing rain particles when they impacted the surface. This observation was confirmed several times during the experiment.

The striking observation in Fig. 2 is the cyclic pattern of \( T_{b} \) between days 359 and 361. Ice thickness was less than 4 cm during that period. A similar cycle was observed in the 2005 data, also for the same thickness range. This pattern is a manifestation of a cyclic pattern of surface wetness followed by freezing. For thin ice growing in a tank, surface wetness can be attributed to one of two possible scenarios. The first is surface cracks, particularly at the edge of the tank. When water freezes in a confined space, the freezing produces pressure in the water underneath the ice (due to ice expansion). Unless this pressure is relieved, the ice will eventually buckle and crack, causing surface flooding. Cracks usually happen at the edge of
Fig. 1. Outdoor ice tank with the two radiometers shown in the background.

Fig. 2. Evolution of radiometric measurements along with atmospheric and surface temperature from December 22 to 28, 2001.
the tank but can happen anywhere. Pressure-relief valves [13] are usually used in laboratory-grown ice tanks; however, they were not used in this experiment.

The second scenario entails the mechanism of brine expulsion to the surface [14]. As ice temperature decreases, more ice will freeze on the walls of the brine pockets, causing shrinkage of their size. The salinity of the remaining brine will increase to maintain both phase equilibrium of the brine and thermal equilibrium with the surrounding ice. However, considering that the newly frozen ice around the pocket has about 10% greater volume than the water from which it froze [15], pressure increases in the pockets, causing brine expulsion. The expulsion is mostly downward into the warmer temperature water; however, it is more upward in the case of thin ice. This liquid brine film at the surface causes the sharp drop in both horizontally and vertically polarized brightness temperatures $T_{bh}$ and $T_{bv}$, as shown in Fig. 2, followed by a gradual increase as the surface starts to refreeze. A previous study [3] reported a drop in $T_{b37}$ when the ice thickness was between 1 and 2 cm with warm liquid brine on the surface. The sharp drop in $T_i$ is associated with a similar sharp increase in the polarization ratio (PR), followed by a gradual decrease (not shown in the figure). The PR is defined as the difference between the vertical and horizontal $T_{bh}$’s divided by their sum. Observations have shown that the peak value of the PR from the 19- and 37-GHz channels during this early stage of ice growth was 0.2, and from the 85 GHz channel, it was 0.1. In general, PR from 85 GHz was almost always half the value from the other two channels, and none of them was a function of ice surface temperature or snow thickness.

The sharp drop in $T_{bh}$, which is associated with an increase in PR, was also observed under two other conditions. The first was when the bare-ice surface started to melt or immediately after snow started to fall (provided that the surface temperature was higher than $-5^\circ\text{C}$). The second was when snow started to fall on newly formed ice (a few millimeters thick). This latter event results in the formation of a snow ice crystalline structure, which is characterized by isotropic crystals with a diameter less than 1 mm (similar to observations reported in [8] and [16]). This ice crystalline structure usually retains significant brine. The surface salinity in the present data, in this case, was typically 35 ppt. As snow continued to fall, it melted and created a thin liquid brine layer which generated microwave emissions similar to that from water. A conclusion from the aforementioned observations is that $T_{bh}$ decreases sharply in response to surface melt. In nature, in addition to the aforementioned scenarios, a thin sea-ice surface becomes wet or flooded if submerged under heavy snowfall.

Fig. 3. Evolution of radiometric measurements along with atmospheric and surface temperature from November 29 to December 5, 2005.
Fig. 3 shows the evolution of $T_b$ during the period November 29–December 5, 2005 (day 333–339). Day 333 featured rain on a candled-ice surface. The $T_b$ from all channels was highly erratic, particularly from the horizontally polarized radiation. This is mainly due to the high spatial and temporal variations of surface properties and geometry. Under this condition, it is impossible to retrieve surface parameters. By the early morning of day 334, all the ice had melted, and the $T_b$ compared well with typical values from seawater (as reported in Section III-B and as shown in Fig. 6). However, during a short period of rain on December 1 (around 335:20.19 in Fig. 6), the $T_b$ from all channels increased with significant fluctuations, particularly from the horizontal polarization, with a noticeable decrease in PR. This observation was particularly pronounced in the 85-GHz data. The average values of PR$_{37}$, PR$_{57}$, and PR$_{85}$ during the rainfall were 0.22, 0.18, and 0.06, respectively, compared with the typical values of 0.30, 0.28, and 0.19 from a smooth water surface. The decrease in PR due to rain causes open-water pixels to be misidentified as ice pixels by most ice-concentration retrieval algorithms. No parallel change in any of the gradient ratios (GRs) (see definition in Section III-C) was noticed. In an early study [17], the effect of rain on microwave emission from the ocean surface was modeled and was noticed. In an early study [17], the effect of rain on microwave emission from the ocean surface was modeled and was noticed. In an early study [17], the effect of rain on microwave emission from the ocean surface was modeled and was noticed.

As refreezing of the water in the tank started in the early hours of day 337 (around 5:00 am) and proceeded gradually to cover the entire tank by the end of the day, $T_b$ increased as expected (with mild fluctuations). A photograph of the ice surface at the onset of freezing, obtained at 14:45 (close to the time mark 337:15:15 in the figure), is shown in Fig. 4(a). The tank was partially covered with thin ice of a few millimeters thick. Surface salinity was around 28 ppt. The fluctuations of $T_b$ during freezing were probably due to the mobility of the small circular ice pieces (pancakelike shape, although they do not fit the WMO’s definition of pancake ice) which are visible in the photo. The beginning of the snowfall on day 338 (338:06:16) resulted in a sharp drop in $T_b$. The ice thickness was only 0.6 cm with surface salinity of 20 ppt and temperature of $-3^\circ$C. Hence, the snow melted as soon as it touched the surface, causing the sudden drop in $T_b$. Eventually, the slushy surface started to freeze (339:12:39), and $T_b$ started to increase monotonically with a higher rate for the 19- and 37-GHz observations. The optical depth of saline ice at those frequencies is 1-3 cm and decreases to about 2–3 mm at 90 GHz [2]. A photograph of the surface at 15:56 is shown in Fig. 4(b).

A more complicated surface process was observed when ice layering started to develop within the snowpack. This situation started on December 25, 2005 (day 359) (not shown in the figure). On that day, the ice and snow column featured 6-cm snow on top of the 2-cm ice layer, followed by 6 cm of slush then another 2 cm of ice layer and 6 cm of dry snow with large crystals, all on top of 15-cm-thick sea ice. Freezing rain fell on this complex surface on day 362 when the surface temperature was around $-2^\circ$C. Fig. 5 shows the evolution of $T_b$ from that day to day 364. The freezing rain melted, causing the $T_b$ to decrease with an increasing polarization difference (point 363:15:33). PR reached a significantly high value (around 0.18) from 19 GHz and lower values of 0.1 and 0.05 from the 37- and 85-GHz channels, respectively. Shortly after, the atmospheric temperature started to decrease almost monotonically from $0^\circ$C to $-20^\circ$C over the next 40 h. As a result, another (third) ice layer was formed at the top of the snow. The refrozen surface caused the $T_b$ from all channels to increase (starting at 364.04:03). By the end of the 40-h period (not shown in the figure), PR-19 decreased to 0.1; however, PR-37 remained at 0.1, and PR-85 increased to 0.08. For the remaining period of the experiment (until January 10, 2006), as the snowpack featured three ice layers, the mean value of PR from the three channels, 19, 37, and 85 GHz, were 0.082, 0.062, and 0.041, respectively, with standard deviations 0.031, 0.033, and 0.026, respectively. This was an increase from the typical value of 0.02 for bare ice or dry-snow-covered ice from any channel. The increase is a result of a decrease in $T_b$ by 20 K–30 K in the 19- and 37-GHz observations and about 15 K in the 85-GHz one, while $T_b$ remained constant. This confirms an early finding in [18] that ice layering within the snowpack causes a decrease in $T_b$ and, hence, an increase in PR. The present results reveal that the same conclusion applies to the 37-GHz observations and, with much less extent, to the 85-GHz observations.

The 85-GHz observations are most sensitive to precipitation on snow-covered ice. When freezing rain and ice pellets fell on the surface (not during the period shown in the figure), the horizontal emission from the 19- and 37-GHz channels was not affected; however, the vertical emission dropped by roughly 8 K or less. On the other hand, both horizontal and vertical emissions from the 85-GHz channel decreased significantly (by 20 K–30 K). The PR, however, maintained the same value of around 0.03. This is an indication of the sensitivity of the 85-GHz radiation to the randomly oriented metamorphosed snow grains at the snow surface and in the volume.

No correlation of $T_b$ with snow thickness was observed from any channel. However, when snow accumulation exceeded 6 cm, the $T_{b_{85}}$ dropped to values lower than those from 37 and 19 GHz. This drop confirms a previous conclusion [19] that snow begins to have an effect on microwave emissions at frequencies above 37 GHz. These effects are driven by the snow grain size and orientation and their contribution to volume scattering. $T_{b_{85}}$ can then be used to determine if the ice surface is snow covered or not.

### B. Emissivity of Different Surfaces

A thin-ice surface reveals a wide range of microwave radiative behavior [5]. In an early study [20], it was reported that two classes of thin ice (not part of the WMO definitions) could be distinguished from the 37- and 90-GHz data. In this paper, an attempt was made to define the radiometrically different surfaces of thin ice in the ice tank. Temperature profiles through the entire snow depth were sampled every 30 min. They were
used to calculate the emissivity of the radiating layer simply by dividing the observed brightness temperature by the average physical temperature of the layer. The latter was roughly estimated for each channel and each surface. Emissivity can be more accurately defined by including the sky brightness temperature \( T_{\text{sky}} \) using the expression \( \frac{T_b - T_{\text{sky}}}{T_s - T_{\text{sky}}} \), where \( T_s \) is the surface temperature. This definition, however, was not used because no continuous record of \( T_{\text{sky}} \) was obtained.

Emissivity values were grouped to examine their differences for the following six different thin-ice surfaces plus water: wet bare ice, wet slush, refrozen slush, wet snow, dry snow, and dry bare ice. The surface type was identified visually or through sampling once or twice per day. The dry ice surface was observed only when the ice thickness was \( > 10 \) cm. Only 69 observations of this surface were made during the 2001 experiment and 83 observations during the 2005 experiment.

In contrast, hundreds of observations were made of each other category. Emissivity was calculated from temperature data obtained within 4 h of the visual observations. No detailed measurements of microscale parameters (e.g., snow wetness, snow layering or grain structure, surface roughness, etc.) were conducted; hence, the following results should be interpreted given the limitations of the visual identification of the surface. Fig. 6 shows the mean and standard deviation of emissivity for each surface.

As expected, water is associated with the lowest emissivity, while the dry surface (bare or snow-covered ice) is associated with the highest emissivity. The variability of each radiometric observation within each surface category is attributed to the variation of the aforementioned snow and ice parameters. For example, dry snow depth in this data set varied between 5 and

Fig. 4. Photographs of the surface (top) at the onset of freezing on December 3, 2005, and (bottom) when the slushy surface started to freeze on December 5, 2005.
20 cm, while its surface temperature varied between $-20^\circ C$ and $+2^\circ C$. The exceptionally high variability of $T_{b_{19h}}$ from the wet bare-ice surface is attributed to the fact that this surface category often includes very thin ice (a few centimeter thick) for which a 19-GHz emission can originate from the underlying water.

It is reported in [21] that emissivity from the 19-GHz horizontal channel is particularly sensitive to inhomogeneities such as a buried crust layer within the snow, and this causes errors in using data from this channel to estimate ice concentration. The present results show that emissivity from horizontally polarized observations exhibits more variability than vertically polarized observations, and that applies to all surface conditions, as shown in Fig. 6. The only exception is the higher variability of $T_{b_{85v}}$ from dry snow cover. It is interesting to note that the emissivity of dry snow from the 85-GHz data (vertical or horizontal polarization) is lower than that from wet snow, with higher variability. This higher variability of the emissivity of dry snow cover compared with the dry ice surface for the 85-GHz radiation is confirmed in [2]. It is probably due to an increased volume scattering within the snow as the snow metamorphoses into coarse grains comparable in size with the wavelength of the 85-GHz radiation. Coarse-grained and icy crust formations on top of the snow were observed during melt–freeze cycles at different periods during the experiments. That affects the conductive heat flux through the snow column and, hence, its wetness and emissivity. In interpreting the variability of emissivity in the data shown in Fig. 6, it should be noted that the snow depth in this data set varied between 5 and 10 cm and the surface temperature varied between $-11^\circ C$ and $+2^\circ C$. These ranges are associated with different processes and surface conditions at the wavelength scale. The emissivities from the horizontally polarized 19- and 37-GHz data were most sensitive to ice surface conditions, particularly wet surfaces.

In general, emissivity increases as the surface becomes dryer. Fig. 6 shows that, from the radiometric point of view, emissivity from open water is different than all thin-ice surfaces at all frequencies and polarizations, particularly from the lower frequencies and the vertical polarization. Moreover, the thin-ice surface can be grouped into the following two radiometrically distinguished categories: 1) wet slush and wet bare-ice surface; and 2) wet snow, dry snow, and dry bare ice, with higher radiation from the second category. Refrozen slush surface appears to fall between these two categories. This confirms the common notion that microwave emission increases as the surface solidifies. Results show that the difference between radiation from wet and dry snow cover is insignificant (based on the visual assessment of snow wetness).
For dry surfaces of bare ice or frozen slush, it was found that the emissivity decreased monotonically as the difference between the subsurface temperature (2 cm under the surface) and the atmospheric temperature just above the surface increased (Fig. 7). The atmospheric temperature for this data set varied from $-5 \degree C$ to $-12 \degree C$. The temperature gradient in the upper 2 cm determines the macroscopic parameters, such as the size of the brine drainage channels, and, hence, the dielectric constant [22]. No similar correlation was found for data from a snow-covered surface (wet or dry) or from wet bare ice or slush. No correlation was found for the higher frequencies considering that the penetration depth is less than 2 cm.

C. Discrimination Between Surface Types

In order to examine the capability of radiometric parameters in discriminating between the seven surfaces defined earlier, plots of the mean and standard deviation of $T_b$, PR, the GR, and the difference in gradient $\Delta GR$ were produced for each surface (Fig. 8). The GR is the difference between the $T_b$ at two frequencies and the same polarization divided by their sum, and $\Delta GR$ is the difference between the horizontal and vertical GRs. The GR between $T_{b\beta\gamma}$ and $T_{b\alpha\gamma}$ is denoted as $GR_{37V19V}$.

For the 19- and 37-GHz channels, $T_b$ from the water does not overlap with $T_b$ from any ice surface [Fig. 8(a)]. This is the reason that most ice-concentration retrieval algorithms [23]–[25] use observations from these two channels. Brightness temperatures from the 19- and 37-GHz channels offer a reasonable separation between the following three surface categories: open water; slush and wet bare ice combined; and wet, dry snow, and dry ice surfaces combined. Brightness temperatures from the horizontal polarization have their mean values spread over a wider range but with higher variability compared with the vertical polarization.

For the 85-GHz channel, the emission from water overlaps with the emission from the wet slush surface. None of the examined $T_b$’s can be used to uniquely identify any of the six ice surfaces. The overlap is particularly pronounced in the 85-GHz vertical polarization. This represents a difficulty in characterizing open water or ice types in the 85-GHz
Fig. 8. Mean and standard deviation of four sets of radiometric parameters from ice surface categories and open water.

Observations with a single value (tie point). It is worth mentioning that part of the high variability of open water from the 85-GHz observations in this data set can be due to the effect of rainfall on the water surface, as mentioned in Section III-A.

Fig. 8(b) shows that the PR $P_{19}$ or $P_{37}$ is almost as good as the brightness temperature in discriminating open water and ice types as the brightness temperature. While the brightness temperature from 85 GHz (particularly from vertical polarization) is useless in discriminating open water and ice, $P_{85}$ can be used successfully for this discrimination. For all surfaces, PR decreases as the frequency increases. The grouping of the different thin-ice surfaces into the aforementioned two categories is confirmed in the PR data from all channels, particularly from the 19-GHz observations.

The best GR parameters that separate water from thin-ice surfaces are $GR_{85V37V}$ and $GR_{85V19V}$ [Fig. 8(c)]. On the other hand, $GR_{37V19V}$ is the most difficult parameter. The GR between any two channels is lowest for dry surfaces (bare ice or snow). They increase as the surface becomes wet and reach their highest value for wet slush. $GR_{85V19V}$ can be used to resolve ambiguity between water and wet slush. However, the problem of using this parameter from satellite observations is the significant difference between the footprints (13 km × 15 km from 85 GHz versus 28 km × 37 km from 37 GHz in the SSM/I data), which makes the contents of each footprint different. The difference between vertical and horizontal gradients “delta gradient” from any channel [Fig. 8(d)] is not useful as a discriminator, even between water and ice. The monotonic increase of this parameter is observed as the difference between the two frequencies increases. On the other hand, the GR decreases as the surface becomes drier. This ratio $\Delta GR_{85-19}$ was used in [26] to identify conditions of surface glaze and layering on first-year ice. The current results, however, did not confirm the potential of this use.

D. Retrieval of Ice and Snow Parameters From Passive Microwave Data

The two most commonly retrieved ice parameters from passive microwave data are ice concentrations and ice-type distribution (only in coarse classes — first-year versus multiyear ice). An attempt to retrieve ice thickness is presented in [27]. Other attempts to retrieve snow depth are presented in [28] and [29]. The current data set was used to assess some of those methods.

As for ice thickness, the study in [27] showed that both PR ($P_{19}$) and the ratio between the 37- and 85-GHz vertical polarizations ($T_{b_{37V}}/T_{b_{85V}}$) were correlated with in situ sea-ice thickness measurements acquired from the Sea of Okhotsk. Therefore, a fairly accurate estimate of ice thickness was obtained from a multiple regression using these two parameters. Details of surface conditions, however, were not presented. This paper has shown that correlations exist only when the surface is dry bare ice or slush (wet or refrozen) but not when it is...
snow covered (Table I). The combination of the two parameters enhances the ice thickness estimate. Note that a dry ice surface in the current experiment was associated with an ice thickness ≥ 10 cm (Section III-B) with a relatively constant surface salinity. When PR_{85} was examined instead of PR_{19}, the correlation values were marginally better. The aforementioned parameters may be used to estimate snow-free ice thickness, whether the surface is dry or slushy. It should be noted, however, that the aforementioned correlation depends on other factors such as ice growth rate (which determines the surface salinity), air temperature history, ice deformation, oceanic heat flux, and, probably, other random disturbances. Hence, the universality of the aforementioned correlations has yet to be established.

The gradient GR_{37V19V} was used to estimate the snow depth over first-year ice through a simple linear regression between the two parameters [29]. This is based on the assumption that 37 GHz vertical is more affected by scattering within the snow than the 19-GHz one. Using a series of observations obtained from the last 12 days in the 2005 experiment, when 4–20 cm of dry snow gradually accumulated on top of the 25-cm thick ice, no evidence of such correlation was observed.

The present observations were also used to evaluate the performance of four ice-concentration algorithms to retrieve thin-ice concentration. They are as follows: NASA Team for Thin Ice (NT-Thin) [24], Enhanced NASA Team (NT2) [26], SEA LION [30], and ARTIST sea-ice algorithm (ASI) [31]. For most of the experiment period, the true ice concentration was 100%. Considering that atmospheric parameters did not influence the radiometric observations, any deviation of the output from a 100% concentration can be attributed to surface conditions. Tie points required to run each algorithm were obtained from the current observations under clear sky with dry ice/snow surface. Three surfaces were used, namely, open water, thin ice (< 10 cm), and thicker ice (> 10 cm).

The NASA triangle for these tie points (in the PR_{19}/GR_{19V37V} space) is shown in Fig. 9, along with the distribution of the two parameters obtained from different surface conditions at different periods during the experiment. On December 8, 2005, the ice was 4 cm thick with a snow-free surface. The corresponding distribution [Fig. 9(b)] is spread over a narrow range between the thin ice and the thicker ice tie points. This ensures a fairly successful ice-concentration retrieval. During the snowfall on December 9, 2005 [Fig. 9(c)], PR_{19} was significantly below the tie point of thin ice; however, when the temperature rose after the snowfall to reach the ice melting point, the distribution spread over a very wide range. This is a situation where the calculation of ice concentration fails. The same situation is depicted in the data of December 16, 2005 [Fig. 9(d)], when heavy snow (17 cm) fell. After the

### Table I

<table>
<thead>
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<th>Surface type</th>
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<th>wet bare ice</th>
<th>refrozen slush</th>
<th>Wet slush</th>
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### Table I: Correlation Coefficient Between Selected Derived Radiometric Parameters and Total Ice and SnowThicknesses

For most of the experiment period, the true ice concentration was 100%. Considering that atmospheric parameters did not influence the radiometric observations, any deviation of the output from a 100% concentration can be attributed to surface conditions. Tie points required to run each algorithm were obtained from the current observations under clear sky with dry ice/snow surface. Three surfaces were used, namely, open water, thin ice (< 10 cm), and thicker ice (> 10 cm).

The gradient GR_{37V19V} was used to estimate the snow depth over first-year ice through a simple linear regression between the two parameters [29]. This is based on the assumption that 37 GHz vertical is more affected by scattering within the snow than the 19-GHz one. Using a series of observations obtained from the last 12 days in the 2005 experiment, when 4–20 cm of dry snow gradually accumulated on top of the 25-cm thick ice, no evidence of such correlation was observed.

The present observations were also used to evaluate the performance of four ice-concentration algorithms to retrieve thin-ice concentration. They are as follows: NASA Team for Thin Ice (NT-Thin) [24], Enhanced NASA Team (NT2) [26], SEA LION [30], and ARTIST sea-ice algorithm (ASI) [31]. For most of the experiment period, the true ice concentration was 100%. Considering that atmospheric parameters did not influence the radiometric observations, any deviation of the output from a 100% concentration can be attributed to surface conditions. Tie points required to run each algorithm were obtained from the current observations under clear sky with dry ice/snow surface. Three surfaces were used, namely, open water, thin ice (< 10 cm), and thicker ice (> 10 cm).

The NASA triangle for these tie points (in the PR_{19}/GR_{19V37V} space) is shown in Fig. 9, along with the distribution of the two parameters obtained from different surface conditions at different periods during the experiment. On December 8, 2005, the ice was 4 cm thick with a snow-free surface. The corresponding distribution [Fig. 9(b)] is spread over a narrow range between the thin ice and the thicker ice tie points. This ensures a fairly successful ice-concentration retrieval. During the snowfall on December 9, 2005 [Fig. 9(c)], PR_{19} was significantly below the tie point of thin ice; however, when the temperature rose after the snowfall to reach the ice melting point, the distribution spread over a very wide range. This is a situation where the calculation of ice concentration fails. The same situation is depicted in the data of December 16, 2005 [Fig. 9(d)], when heavy snow (17 cm) fell. After the snowfall, the distributions of the two parameters again occupied a wide range, perhaps due to snow metamorphism which is driven by many factors, including vertical temperature gradient, overlaying pressure, humidity, and brine migration upward through snow [32]. This unsettled period extended almost 8 h after the snow ended. The retrieval of ice or snow parameters from microwave observations would not be possible during this period. Data from a very wet snow surface, obtained on December 18, 2005 [Fig. 9(e)], also show a relatively wide distribution and, hence, possible error in estimating the ice concentration. Toward the end of the 2005/2006 experiment, when the ice thickness was 23 cm with cold, dry, and stable snow cover, the distribution centered around the tie point of the “thicker ice” [January 7, 2006, in Fig. 9(f)]. This ensures a successful application of the algorithms that employ the concept of the tie point.

The aforementioned discussions highlight the fact that using tie points in ice-concentration retrieval algorithms will fail if ice/snow surface processes (brine migration, snow metamorphism, etc.) are active at a short time scale. This is mostly the case of thin ice, with its sharp temperature gradient through its depth, although it also happens with thick ice during wet precipitation or freezing rain events. The selection of more than one tie point to represent an ice surface type would be an appropriate approach; however, it should be followed by some sort of averaging of the results from using different values of tie points.

Fig. 10 shows the ice-concentration output from the four algorithms for the period December 17–26 (days 342–351). On the first day, the ice was 4 cm thick with a snow-free surface. NT-Thin, NT2, and ASI underestimated the concentration slightly in the beginning, then produced the correct 100% concentration. SEA LION initially produced the correct 100% concentration. When snow started to fall early on day 343 and then turned into 1 cm of slush throughout days 344 and 345, NT-Thin and NT2 underestimated ice concentration (between 40% and 70%) with moderate fluctuations. The reason is probably due to the deviation of the observation from the tie points, which were established using observations from dry ice surface. The SEA LION output switched between 0% and 100% concentrations. This is perhaps caused by the algorithm’s iterative process that couples the concentration estimates with correcting the observations for meteorological influences. It is possible that the process terminates before convergence to the specified threshold of the concentration difference between successive iterations. In this case, the output is truncated to 0% or 100% concentration. ASI produced low concentration values (between 0% and 60%) with strong fluctuations.

The slushy surface started to freeze later on day 346. By the end of day 348, the ice thickness reached 11 cm with a
stable frozen slush surface. During this period, NT-Thin and NT2 ice-concentration outputs increased gradually to reach the correct 100% value. SEA LION produced the correct value, while ASI continued to produce lower values (between 10% and 70%). Snow, ice pellets, and freezing rain started in the early hours of day 350 and accumulated to 17 cm by day 351. NT-Thin and NT2 severely underestimated the concentration with fluctuations between 20% and 90%. Both SEA LION and ASI output 0% concentration during the precipitation event and increased afterward. ASI produced 0% ice concentration when the polarization difference between the 85-GHz channels is small. This situation was frequently encountered in the current data, and it can be corrected by modifying the equation that determines the concentration as a function of polarization difference in the algorithm. This is an empirical equation that did not apply well to the current data.

When the atmospheric temperature approached 0 °C by noon of day 351 and surface flooding was observed, the output from all algorithms was less than 100%, with strong fluctuations. When the temperature started to decrease gradually below zero, the concentration started to increase toward the correct 100% value. During the last ten days of the experiment (January 1–January 10, 2006), the ice was 22–24 cm thick, with 20 cm of snow and frozen slush at the surface. All algorithms except ASI produced the correct 100% concentration. NT2 and NT-Thin produced 100% concentration, while ASI produced values between 10% and 70%.

Table II includes the percentage of correct output (concentration ≥ 90%) and the wrong output (concentration ≤ 10%) from the data set of 2005. It can be seen that the NT-Thin algorithm produces the best overall results, followed by NT2, then SEA LION and ASI. It is worth mentioning that the last two algorithms use 85-GHz observations. In general, the accuracy of the calculated ice concentration is more affected by the stability of the surface conditions rather than the ice thickness. For example, it was found that all algorithms underestimate the ice concentration if the surface is wet or if snow metamorphosed into large crystals. The thick ice surface
is more stable in terms of its salinity and snow metamorphism, mainly due to the milder temperature gradient between the warm water underneath the colder atmosphere. All algorithms failed to produce the observed 100% ice concentration when the ice was ≤ 4 cm thick.

IV. Conclusion

Artificial sea ice was grown in an outdoor tank located at the National Research Council in Ottawa, Canada, during two winter seasons — 2001/2002 and 2005/2006. Ice reached 25-cm thickness in both experiments. Microwave emission from the following three spectral channels: 19, 37, and 85 GHz was sampled every 5 min, and surface measurements were obtained to explain the radiometric behavior of the thin-ice surface.

One observed radiometric characteristic of very thin ice (< 5 cm thick) is a cyclic pattern of sharp drops in the brightness temperature followed by a gradual increase. This is in response to the first instant of any possible mechanism of surface wetness followed by surface refreezing. This was observed in
both experiments from all channels; however, the drop in the 85-GHz observations was more significant than the other two channels. Results also revealed that microwave radiation from thin ice is particularly sensitive to meteorological factors. For example, radiation from all channels, particularly horizontally polarized ones, showed a highly random behavior during rain, freezing rain, and, to some extent, snowfall on ice < 10 cm thick. Surface conditions caused by these events (e.g., physical composition, temperature, and salinity) vary considerably.

Emissivity from horizontally polarized observations exhibit more variability than vertically polarized observations, and it applies to all surface conditions. The thin-ice surface can be grouped into two radiometrically distinguished subcategories, namely, 1) wet slush and wet bare-ice surface; and 2) dry snow, dry snow, and dry bare ice, with higher radiation from the second category. In terms of microwave emission, the refrozen slush surface appears to fall between these two categories. This confirms the common notion that microwave emission increases as the surface solidifies. The difference between the radiation from wet and dry snow covers is insignificant in lower frequency channels (19 and 37 GHz). The distinction between water on one hand and all ice surface types on the other hand can be made using two frequency channels. Results also revealed that microwave radiation from 85-GHz observations was more significant than the other two frequency channels. The overlap between radiometric measurements from ice surfaces is most severe in the 85-GHz observations.

The present observations were used to evaluate existing methods of ice and snow thickness retrieval, as well as ice concentrations. It was found that PR 19 and the ratio \( T_{23}\frac{T_{20}}{T_{20}} \) are useful in retrieving total ice and snow thickness but only when the surface is covered by dry ice or refrozen dry snow. Limitations in retrieval of any thin-ice parameter should be established in terms of surface composition, not ice thickness. Four algorithms of ice-concentration retrieval (NT-Thin, NT2, SEA LION, and ASI) were examined for their potential of retrieving concentrations of thin ice with different surface conditions. They generally failed to produce the apparent 100% concentration in the tank when the ice thickness was less than 10 cm due to the complicated surface conditions. Overall, the NT-Thin algorithm produced best results, and ASI produced the least precise results.

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