Ice Sheet Surface and Subsurface Melt Water Discrimination Using Multi-Frequency Microwave Radiometry

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Abstract For understanding englacial hydrology and its impact on ice sheet mass balance, observations of the liquid water content (LWC) within the ice sheets are needed. We combined 1.4–10.7 GHz passive microwave measurements with traditional 18.7–36.5 GHz measurements to detect subsurface LWC. In situ measurements from the DYE-2 experiment site in Greenland and a modeled LWC at this site were used to calibrate and validate the method. Our analysis showed sensitivity of the lower microwave frequencies to LWC in surface and subsurface layers down to at least 2 m, enabling detection of seasonal subsurface LWC and its refreezing. A simplified retrieval detected a delayed refreezing of subsurface LWC following surface freezing, while also capturing total seasonal meltwater production. These advancements open the door to detection of subsurface meltwater and refreezing twice a day at pan-Greenland scale, thereby enabling improved estimates of ice sheet contributions to global sea level rise.

Plain Language Summary Large areas of Earth’s ice sheets experience significant seasonal melting, produced by the seasonally warming atmosphere and increasing solar radiation, that starts a complex chain of liquid water infiltration, retention and refreeze processes. These processes are tracked with satellite-based methods, which are largely limited to detecting near-surface meltwater only. However, in order to fully understand the impact of meltwater on the evolution of the ice sheets, the intrusion of meltwater into deeper ice layers needs to be characterized. Therefore, in this study, we investigated combining lower frequency passive microwave measurements with traditionally applied higher frequency measurements to detect meltwater into deeper layers of the Greenland ice sheet. Our analysis showed that the lower microwave frequencies are sensitive to meltwater in surface and subsurface ice layers down to at least 2 m at the DYE-2 experiment site in Greenland, where meltwater was observed using sensors installed down to a depth of about 4 m. A simplified multi-frequency meltwater retrieval approach demonstrated the detection of delayed refreezing of subsurface layers after an earlier surface refreeze, while also capturing the total seasonal meltwater. These results enable significant improvement for ice sheet meltwater monitoring.

1. Introduction

The Greenland ice sheet is a major and increasingly important contributor to global sea level rise through the melting and calving of its ice masses (e.g., Frederikse et al., 2020; Golledge et al., 2015; Shepherd et al., 2018; Slater et al., 2021). Monitoring and understanding its evolution is required to estimate the amount of meltwater that escapes to surrounding oceans rather than remains as refrozen water in land ice. The ice sheets experience significant seasonal surface melt events that start a complex chain of liquid water infiltration, retention, and refreeze processes (e.g., Nghiem et al., 2012; Picard et al., 2007). For the ice sheet mass balance estimation, understanding these processes is critical (Janssens and Huybrechts, 2000) and mass balance model studies would particularly benefit from improved initialization of liquid water at the surface (van As et al., 2016). Many mass balance models depend on inferred liquid water distribution in the snow and firn based on albedo and snow/firn structural parameters (such as density and pore space, which affect hydraulic and thermal conductivity) in absence of measured values (e.g., Langen et al., 2017). Microwave radiometry in the right frequency range is an effective tool for detecting melt because of its sensitivity to the change of the permittivity of the ice sheet during melt events (e.g., Abdalati and Steffen, 1995; Das and Alley, 2003; Liu et al., 2005; Zwally and Fiegles, 1994). Furthermore, currently operating satellite microwave radiometers image the polar ice sheets several times a day (a single satellite typically passes over a location once or twice daily) in almost any weather condition because
of their low sensitivity to atmospheric cloud/aerosol and solar illumination constraints. This results in reliable time-series of melt signatures at 10–40 km resolutions, depending on the instrument (e.g., Fettweis et al., 2006; Tedesco, 2007, 2009). The retrieval approaches have traditionally used the 18.7 and 37 GHz frequency bands (Jezik et al., 1993; Mote, 2003; Mote and Anderson, 1995; Steffen et al., 1993). The measurement record at these frequencies has now reached a climatologically meaningful record of surface melt statistics (e.g., Fettweis et al., 2011). Continuing observations are now routinely used to track current melt status (e.g., NSIDC, 2021) as well as long-term trends in melt extent (e.g., Colosio et al., 2021).

However, while significant progress is being made using these approaches, our understanding of ice sheet melt is limited by current observational melt products. Existing 18.7 GHz and 37 GHz-based products report only the top layer (at most the first 50 cm) of surface melt and do not convey information on deeper (below 50 cm) subsurface melt/refreeze processes (e.g., Tedesco, 2015). This is due to the relatively high frequencies used in the retrievals, for which only the radiation emanating from the near surface snow (and firn) layers reach the satellite (radiation at these frequencies emanating from deeper layers is extinguished by overlying layers). Recently, 1.4 GHz observations have been introduced for the detection of surface melt (Houtz et al., 2021; Leduc-Leballeur et al., 2020; Mousavi et al., 2021, 2022) in addition to detecting meltwater stored in deeper perennial firn aquifers (Miller et al., 2020, 2022). These studies suggest that 1.4 GHz measurements are sensitive to deeper-layer volume emissions, even in the presence of some overlying wet snow and firn. The 1.4 GHz brightness temperature (TB) measurements are available from the ESA SMOS (Soil Moisture Ocean Salinity) mission (launched in 2009; Mecklenburg et al., 2016) and NASA SMAP (Soil Moisture Active Passive) mission (launched in 2015; Entekhabi et al., 2014) satellites. Additionally, 6.9 and 10.7 GHz (along with 18.7, 36.5 and 89 GHz) TB measurements became available with the launch of the JAXA AMSR-E instrument on the NASA Aqua satellite in 2002 (Kawanishi et al., 2003) and have continued with AMSR2 on GCOM-W1 (Imaoka et al., 2010). However, no current melt detection methods exploit the full range of frequencies available from these operational satellites to retrieve liquid water content (LWC) information for different depths of the snow/firn column.

Therefore, in this study, we set out to investigate a multi-frequency combination of SMAP (1.4 GHz) and AMSR2 (6.9, 10.7, 18.7, and 37 GHz) TB measurements for retrieving information on surface and subsurface melt conditions. The study focuses on the DYE-2 experimental site in Greenland, for which Samimi et al. (2021) used in situ temperature and LWC observations at depths down to 5 m to calibrate an energy balance model that provides direct estimates of the LWC distribution in the subsurface snow and firn. We used both the in situ observations and the modeled LWC to investigate the multi-frequency TB response to the LWC depth profile, with a particular focus on the sensitivity of each frequency to LWC at varying depths.

### 2. Data and Methods

#### 2.1. SMAP and AMSR2 Microwave Radiometer Processing

The SMAP L-band radiometer has measured vertical (V) and horizontal (H) polarized 1.4 GHz TB with native 38-km resolution (Piepmeier et al., 2017) since 31 March 2015. The satellite is on a sun-synchronous orbit with 6 a.m. and 6 p.m. local time equatorial overpasses (Entekhabi et al., 2014). Here, we used the spatially enhanced TB product (LICTBE, version 3) posted to a consistent 9-km equal-area (EASE v2) polar grid (Chaubell et al., 2020). Over the DYE-2 site, the overpasses occurred within 45 min of 7:30 a.m. local time and 4:45 p.m. local time. SMAP LICITBE values in the 9-km grid cell containing the DYE-2 site were used for the analysis. The 9-km polar grid facilitates better co-location between the in situ measurements and overlying satellite grid cell (with respect to footprint size) than the 36-km grid product or the 9-km global grid product.

JAXA’s AMSR2 instrument onboard the Global Change Observation Mission-Water Shizuku (GCOM-W1) spacecraft provides simultaneous V and H polarized TBs at 6.9/7.3, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz frequency with 1:30 a.m./PM local time equatorial overpasses and global coverage since 18 May 2012 (Imaoka et al., 2010). Over the DYE-2 site, the overpasses occurred within an hour of 3 a.m. local time and 12:30 p.m. local time. The AMSR2 3 dB footprint is largest (~41 km) for the 6.9 GHz channel and smallest (~8 km) for the 36.5 GHz channel. The footprint centers are slightly different for each channel. AMSR2 TBs (standard L1B version 2 product with raw resolution) for the DYE-2 location were produced using an inverse-distance-squared weighting algorithm having a 20 km radius around the DYE-2 coordinates.
2.2. Liquid Water Content Profile Retrieval

The TB response to melt events can be attributed to the presence of liquid water within the firn at depths corresponding to the frequency-dependent transmission within the firn (Ulaby and Long, 2014): therefore, multichannel algorithms can provide depth-dependent information (unlike single-channel melt-detection that provides information only about meltwater presence). In order to examine the sensitivity of differing frequencies to the LWC profile, we developed a simplified retrieval approach that considers propagation of microwave emissions through firn layers of different thicknesses as illustrated in Figure 1. We used this five-layer structure in the retrieval model and adjusted the layer thicknesses based on the initial observations of the response of the TB to the LWC profile. The thicknesses of each layer in the five-layer retrieval model were selected based on maximizing the Pearson correlation coefficient between TB and modeled/measured LWC (see Section 3.3).

The TB measurements at each frequency can be normalized between a minimum value observed during fully frozen conditions and a maximum value observed during the melt season. We assume here that the maximum value corresponds to the maximum melt observable at a particular frequency. This normalized TB is then used to define a “saturation fraction” as:

\[ SF_p(f) = \frac{T_{B,p}(f) - T_{B,frozen}(f)}{T_{B,max}(f) - T_{B,frozen}(f)} - a \cdot \frac{1}{1 - a} \]  

where \( SF_p(f) \) is the frequency-dependent saturation fraction and \( T_{B,p}(f) \) represents TB with the subscript \( p \) indicating the polarization; \( T_{B,frozen}(f) \) and \( T_{B,max}(f) \) represent TB during frozen conditions and the maximum TB during the season, respectively, and \( a \) is a rescaling factor that limits observational noise at the lower bound. Cases having saturation fractions less than zero from Equation 1 are reported as saturation fraction zero.

Following Figure 1, we introduce a “top-down” integrated total liquid water amount \( LWA_{T,Dn} \) as an equivalent thickness of liquid water that is computed from the surface to the depth of layer \( n \) within the firn. The LWA of an individual layer is then:

\[ LWA_{n} = LWA_{T,Dn} - LWA_{T,D(n-1)} \]  

where \( LWA_{T,D0} \) is 0. We also define the unitless LWC fraction for individual layer \( n \) of thickness \( \Delta y_n \) as:

\[ LWC_{n} = \frac{LWA_{n}}{\Delta y_n} \]  

In order to estimate \( LWC_n \) from the TB measurements, \( SF_{f(n)} \) is used to scale \( LWA_{T,Dn} \) between zero and \( LWA_{T,Dn}^{\text{max}} \) as:

\[ LWA_{T,Dn} = SF_{f(n)}LWA_{T,Dn}^{\text{max}} = SF_{f(n)}y_nLWC_{T,Dn}^{\text{max}} \]  

where \( LWC_{T,Dn}^{\text{max}} \) represents the fraction of irreducible water (e.g., Samimi et al., 2021). While Equation 4 implies wetness retrieval through each top-down layer, in reality melt water in the top part of the surface may block emissions coming from the deeper parts of the layer. This creates a blind spot for the retrieval, which is discussed more in Sections 3.3 and 4.

2.3. DYE-2 Site and In Situ Measurements

In April 2016, two observation sites in the near-surface firn were established close to the DYE-2 station, which is located within the percolation zone of southwestern Greenland at 2,120 m elevation. Within a 20-km radius (approximating the radiometer measurement area) of the DYE-2 location, the highest point is about 90 m higher...
and the lowest point is about 140 m lower than the station elevation (Howat et al., 2014). The sites were within 1 km of the Greenland Climate network (GC-Net) automatic weather station established at DYE-2 in 1996 (66°28′50″N, 46°16′59″W; Steffen and Box, 2001). Thermistor and time-domain reflectometry (TDR) arrays were installed in two firm pits that were 400 m apart and 5.3 m (A) and 2.2 m (B) deep (Samimi et al., 2020). Each firm pit was instrumented with eight thermistors and time-domain reflectometry (TDR) probes to monitor snow water content. The sensor spacing was irregular in order to concentrate observations near the surface as well as immediately above and below thick ice layers. The legend in Figure 2c shows the depths of the sensors in each pit. The values were recorded every 30 min from 11 May to 30 September 2016 to capture subsurface hydrological and thermal evolution over the complete melt season.

2.4. Energy Balance Model Based Meltwater Estimates

We used the energy balance model-based melt estimates for the DYE-2 location described in Samimi et al. (2021). In the model, the surface energy balance and melt rates are calculated following the model of Ebrahimi and Marshall (2016), which includes a subsurface model for heat conduction in the upper 20 m of firn and snow. The model has 43 layers, in which layers are 10-cm thick from the surface to a depth of 60 cm, 20-cm thick from 60 cm to 2 m, 40-cm thick from 2 to 10 m, and 1-m thick from 10 to 20 m. In modeling the LWC, the original model-based near-surface (upper 4 m) density, ice content, and temperature were overwritten using the observed values from the firm pits. Below 4 m, the modeled values were used for initial conditions. The parameterization of the energy balance model was calibrated using the firn pit LWC observations. It was noted in this process that the pits used had a significant variability with respect to each other that was taken as an indication of the expected small-scale lateral variability in ice-layer stratigraphy and density in polar firn (e.g., Marchenko et al., 2016; Weinhart et al., 2021). Given the coarse multi-kilometer sampling footprint of the satellite microwave radiometric measurements, we assumed here that the model provides a general landscape representation consistent with the regional meteorology, surface energy balance, and snow conditions. The assumptions and uncertainties of the model are discussed more in Supporting Information S1.

3. Results

3.1. Brightness Temperature Response With Respect to Temperature Measurements

The melt detection approaches using 18.7 and 36.5 GHz channels are based on the large difference in the TB response between frozen winter conditions and the melt conditions during the summer months. In order to investigate whether the lower frequencies respond similarly we looked at the standard deviation of the SMAP (1.4 GHz) and AMSR2 (6.7, 10.7, 18.7, and 36.5 GHz) TB measurements over the DYE-2 site during the frozen and melt seasons. During the winter (frozen) season (1 October 2015–1 April 2016) the standard deviations of V-pol (H-pol) TB measurements for each frequency band were 1.5 K (1.6 K), 4.6 K (3.4 K), 3.0 K (2.2 K), 3.0 K (3.7 K), and 6.8 K (6.1 K), respectively. During the melt season analyzed here (10 May–15 September 2016) they change to 26.2 K (31.9 K), 38.3 K (45.4 K), 37.2 (44.8 K), 33.2 K (39.6 K), and 31.5 K (31.7 K). The result establishes that the 1.4, 6.9, and 10.7 GHz channels exhibit similar seasonal response as the higher frequencies (Figure S1 in Supporting Information S1 shows the TB time-series used in the computation).

Figures 2a and 2b focus on TB V and H polarization measurements from May to September 2016, respectively, and Figure 2c further plots air temperatures as well as snow and firn temperatures measured at multiple depths within the two DYE-2 pits. Temperatures recorded in the two pits are generally consistent in behavior, and show similar warming and cooling trends. During some periods the 10-cm sensor is above 0°C as a result of apparent solar heating and from 19 July to 13 August there are instances when even the 30-cm sensor is above 0°C. The warmest conditions in the snow/firn column occur on 12 August, when the pit A temperature reaches 0°C even at 1.8 m depth. Before and after this event there are several warming and cooling cycles that impact different depths within the snow/firn column. SMAP and AMSR2 TB measurements clearly respond to these changes, with each frequency band ranging between a low value characteristic of frozen conditions and a higher value corresponding to the change in the permittivity of the snow/firn column. Detailed examination further shows that the TB variations in each band correspond to temperature changes at different depths (and the correspondence to the modeled LWC is discussed in Section 3.2).
Figure 2. (a) and (b) SMAP and AMSR2 vertically (V) and horizontally (H) polarized brightness temperature (TB) measurements at 1.4, 6.9, 10.7, 18, and 36.5 GHz frequencies over the DYE-2 site during the melt season of 2016. (c) Air temperature and snow and firn temperature measurements in pits A and B at DYE-2 combined in a single plot. The pit of each sensor is indicated in parenthesis in the legend. (d) Liquid water content profile in the snow and firn from the energy balance model. (e) The total liquid water amount (LWA) based on the model.
For example, the increase in 36 GHz TBs early in the time series corresponds to the air temperature rising above 0°C, during which lower frequencies exhibit a much smaller effect. During this time, temperatures at 10-cm depth did not reach 0°C, indicating that melt occurred only in a very thin surface layer. A similar cycle was observed between 4 and 14 June with increased warming on 10 June when 10-cm and 20-cm temperatures warmed to 0°C. Vertically polarized TBs at 18.7 and 36.5 GHz all reached local maxima soon after the air temperature reached near 0°C, while the evolution of the TBs at 10.7 GHz and especially at 6.9 GHz were slower, reaching a local maximum several days later. The TB at 1.4 GHz during this time had values higher than during the earlier melt, but remained significantly below the seasonal maximum. Horizontally polarized TBs behaved similarly, but the 10.7 GHz response required additional days before reaching a maximum. During the melt event from 9 to 16 June, there was a clear diurnal cycle in both the air temperature and in the TBs observed in all bands. The amplitude of the diurnal cycle is largest at 36.5 GHz, while daily-minimum TBs at lower frequencies remain higher than their frozen season minimum values. This suggests that the lower frequencies were affected by meltwater to which the 36.5 GHz channel was insensitive, that is, subsurface persistent meltwater. This assertion is further supported by the in situ temperature measurements, which show that the 10 and 20 cm temperatures persistently remained at 0°C as the air temperature experienced diurnal cycling so that surface refreeze and melt likely occurred on a daily basis. After 16 June, the refreezing process also affected 36.5 GHz TBs more quickly than at lower frequencies, which required two additional days to return to their “fully frozen” levels. Additional similar diurnal cycle effects are also evident from 17 July to 3 August.

Other warming cycles throughout the melt season show similar behaviors. Both 22 June to 6 July melt/freeze and the 13–22 August refreeze periods show refreeze rates that differ with TB frequency. During the latter period, in situ temperature measurements show that a wedge of 0°C temperatures in the 60–120 cm depth ice layer refroze from both above and below simultaneously. This corresponds to the higher TB frequencies returning to their minima as soon as the top layers started to refreeze while it took longer for the lower frequencies to return to their minimum values. SMAP’s 1.4 GHz measurements reach their maximum only on 12 August, the day that represents the strongest melt during the season. The longest period during which at least one of the temperature sensors exceeds 0°C occurs from 19 July to 21 August. During this period, TBs at 36.5 GHz frequently return to values representative of “surface frozen” conditions, whereas the lower frequency channels considered here provide clear evidence of subsurface melt water.

3.2. Brightness Temperature Response With Respect to Modeled LWC

The model-predicted LWC profile in Figure 2d is generally consistent with the temperature measurements, and shows diurnal variability of LWC in surface layers and persistent wetness in deeper layers corresponding to the TB measurements at different frequencies, as the lower frequencies are affected by both surface and subsurface conditions. During the period around 7 to 14 June, the air temperature abruptly decreased and the 10-cm thermistor remained at the freezing point while the modeled LWC declined to zero, after which the 10-cm thermistor dropped below freezing and roughly tracked air temperature. This example shows that the model accurately predicted that refreezing kept the 10-cm thermistor at 273 K until all the water froze. Figure 2e plots the total snow/firn layer LWA based on the model output, where the maximum LWA occurs on 12 August.

The temporal trends of the 1.4 GHz TB measurements are very similar to those of the total LWA in Figure 2e suggesting that the 1.4 GHz TB can be used to detect the total seasonal melt water. Only during 19 July to 2 August, the subtle evolution of 1.4 GHz TB is opposite to that of the modeled LWA. The higher frequencies, however, have more nuanced response to the LWC at different depths. During 17 July to 3 August period, the model predicts persistent liquid water that extends to 1 m depth as well as liquid water in the first 20 cm depth that goes through a diurnal melt-refreeze cycle. At the start of this period, all bands except 1.4 GHz reach their maximum values. This suggests that the lower frequencies were affected by meltwater to which the 1.4 GHz TB is insensitive, that is, subsurface persistent meltwater. This assertion is further supported by the in situ temperature measurements, which show that the 10 and 20 cm temperatures persistently remained at 0°C as the air temperature experienced diurnal cycling so that surface refreeze and melt likely occurred on a daily basis. After 16 June, the refreezing process also affected 36.5 GHz TBs more quickly than at lower frequencies, which required two additional days to return to their “fully frozen” levels. Additional similar diurnal cycle effects are also evident from 17 July to 3 August.

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melt (1–2 mm) even though the 2-m air temperatures remained below freezing; however, based on the air temperature and TB measurement, the surface likely stayed frozen.

Figure 3a plots the Pearson correlation (R) between V- and H-polarized TB and the model-predicted LWA integrated from the surface to a depth ranging from 10 to 180 cm. The 1-sigma (68%) confidence intervals for the R values (Figure S2 in Supporting Information S1) and their calculation approach are shown in the supplemental information. As expected, the relative R magnitudes of the different frequency bands are greatest at 36.5 GHz for the first layer and at 1.4 GHz for the aggregate of all layers. The 36.5 GHz V(H) peak correlation is at 20 cm (20 cm), while 18.7 GHz peaks at 40 cm (40 cm), 10.7 GHz at 60 cm (50 cm), 6.9 GHz at 80 cm (60 cm), and 1.4 GHz at 80 cm (80 cm). For the 36.5 and 18.7 GHz bands R deteriorates significantly as deeper layers are included, consistent with the expectation of their sensitivity to near-surface meltwater content. Figure 3b further plots V-polarized TBs as a function of the LWA in the two top layers (to 20 cm depth) and in all layers (to 180 cm depth). The low R in the case of all the layers is a clear indication of a breakdown of the relationship between the TB and total 1.8 m LWA. The largest R is achieved by the 1.4 GHz band for the LWA in the 80 cm layer, with a diminished correlation observed as deeper layers are included. The 1.4 GHz TBs plotted in Figure 3c suggest however that the correlation diminishes not because of a breakdown in the TB-LWA relationship (as in the case of the 36.5 GHz band), but because of the more complex water distribution affecting TB in complex ways that degrade the linear Pearson correlation. Below 80 cm there are melting and refreezing cycles (Figure 2d) that seem to be the cause for the hysteresis type of response.

3.3. Liquid Water Content Profile Retrieval

The initial step in setting up the retrieval was to define the top-down thickness of the layers (Section 2.2), which was informed by the correlation analysis discussed in Section 3.2. For example, the maximum 36.5 GHz to LWA correlation was found at 20 cm (Figure 3a), so 20 cm is used for the first layer thickness \( y_1 \). Similarly, 40, 70 (between the 40 and 80 cm maxima), 100, and 180 cm are used for the “top-down” \( y_2 \) to \( y_5 \) thicknesses representative of 18.7, 10.7, 6.9, and 1.4 GHz sensing depths; the latter value is selected to capture the sensitivity to melt observed at 1.4 GHz at 1.8 m. \( LW_{C_{\text{max}}} \) for each layer was roughly estimated from 0.035 to 0.020 (from layer 1–5) based on the modeled vertical profile of the fraction of irreducible water presented in Samimi et al. (2021).

Figure 4a plots the SF for V-polarization determined from Equation 1; results in H-polarization are similar and are not shown. The retrieved LWC profiles are illustrated in Figure 4b; for comparison, Figure 4c illustrates the model-predicted LWC profile averaged to the layer thicknesses shown in Figure 1. The retrieved LWC profile shows features similar to those of the modeled LWC, including the primary melt events and the separation of meltwater between the first and deeper layers. The largest discrepancy in the top layer occurs during 18–23 August, where the energy-based model may overpredict surface melt (Section 3.2). While refreeze trends are also generally well replicated, a clear overestimation of meltwater in the deeper layers occurs during the first half of the melt season. During these melt events, SF values are high for 6.9–36.5 GHz bands and the retrieval predicts meltwater in the deeper layers even though it is the LWC in near surface layers.

Figure 3.

(a) Pearson correlation (R) of the vertically (V) and horizontally (H) polarized TB change with the model-based LWA (liquid water amount) over a variable thickness of the snow/firn column. (b) The change of V-polarized 36.5 GHz TB as a function of aggregated LWA in layers 1 and 2 (down to 15 cm) and in all layers (down to 190 cm). (c) The change of V-polarized 1.4 GHz TB as a function of aggregated LWA in layers 1 and 7 (down to 70 cm) and in all layers (down to 190 cm). The 1-sigma (68%) confidence intervals of the R values are shown in the brackets.
that causes the high SF values. Similarly, LWC is overestimated in the bottom layer at the end of July when the 1.4 GHz SF approached a maximum. The simplified retrieval model is relatively sensitive to the selection of the layer thicknesses and the maximum LWC, which affect the LWA attributed to each frequency and, consequently, the layer-specific LWC values. In particular, when the SF of the highest and subsequent frequencies is near 100%, ambiguities in the assignment of the liquid water to its depth can occur. Nevertheless, the simple retrieval strategy proposed is shown to be capable of providing information on the presence of subsurface liquid water; in particular, under frozen surface conditions.

4. Discussion and Conclusion

Our results indicate two main benefits from combining lower TB frequencies (1.4–10.7 GHz) with higher frequencies (18.7 and 36.5 GHz) for satellite detection and monitoring of ice sheet melt/refreeze events and associated LWC changes: (a) the addition of lower frequency (1.4, 6.9, and 10.7 GHz) observations allow for reliable detection of the presence of sub-surface meltwater when higher frequencies alone would otherwise indicate frozen conditions; and (b) the 1.4 GHz frequency enables estimation of the total seasonal meltwater within the upper layers of the ice sheet. although extremely wet surface conditions not encountered in this study may challenge this performance (Mousavi et al., 2022). The higher TB frequencies were much more sensitive to smaller amounts of meltwater and in a shallower surface layer than the 1.4 GHz channel. The 1.4 GHz TBs exhibited sensitivity to LWA up to about 4 cm in a surface snow/firn layer of about 180 cm depth, while the 36.5 GHz channel saturated at about 0.4 cm LWA in a layer of about 20 cm depth. It is possible that the 1.4 GHz TB response did not fully saturate under the observed LWA range as occurred with the higher frequency channels (which experienced maximum V polarization TB of over 270 K, which is very close to the physical maximum of 273 K when the temperatures of the medium remain at 0°C or below), and the L-band channel could be sensitive to even higher

Figure 4. LWC profile retrieval. (a) Saturation fraction, as defined in Equation 1, for the vertical polarization during the 2016 melt season. (b) Retrieved LWC profile using the simplified model. The retrieved profile has increasing uncertainties with increasing surface LWC, as the signal from the deeper layers is diminished by the LWC effects in the surface. (c) Modeled LWC for the layers defined in Figure 1.
LWA levels and in deeper ice layers (e.g., Miller et al., 2020; Mousavi et al., 2021). These results are not unexpected, but the combination of the satellite data, the in situ observations and the calibrated energy balance model provided convincing evidence of the utility of a multi-frequency approach for meltwater detection.

The 1.4 GHz TB record can now support investigations over more than a decade that includes extreme melt seasons in Greenland in 2012, 2019, and 2021 (Hanna et al., 2014; Mousavi et al., 2021; Sasgen et al., 2020). The 6.9 and 10.7 GHz TB records are further available since 2002. While the time-series available for lower frequencies remain shorter than the four-decade long records available from 18.7 to 36.5 GHz channels, they have accumulated sufficiently to contribute to the analysis of the evolution and rapidly intensifying melting of Earth’s ice sheets. In the current record, the overlap times of the 1.4 GHz measurements (SMAP) and the higher frequencies (AMSR2) are different (6 a.m./p.m. vs. 1:30 a.m./p.m.) which adds to retrieval uncertainties when the measurements are combined. In the future, missions such as ESA CIMR (Copernicus Imaging Microwave Radiometer) are expected to further extend the 1.4–36.5 GHz measurement record and provide measurements at all these frequencies simultaneously (Donlon, 2020).

The simplified multi-frequency LWC retrieval process introduced appears reasonable, but it has a blind spot in predicting liquid water depth when all or most TB channels become saturated. Further analyses using multi-frequency multi-layer emission and energy balance based LWC modeling are therefore recommended to assess conditions under which retrievals of LWC profiles may still be possible. An improved approach could use state-of-the-art multi-layer emission modeling with snow, firn and ice structural information (such as Microwave Emissivity Model of Layered Snowpacks [Wiesmann & Matzler, 1999] or Snow Microwave Radiative Transfer [Picard et al., 2018]) applied to both V- and H-polarization and their combination; utilize energy balance models (such as the Glacier Energy and Mass Balance module within the Ice-sheet and Sea-level System Model (Gardner, 2010; ISSM, 2021)) to obtain information on expected LWC limits, water infiltration, and subsurface refreeze dynamics or even to assimilate with the retrieval algorithm, and also utilize the multi-temporal information available in the twice-daily observations to, for example, constrain parameter and retrieval values. While the results shown here have considered only a single location, it is expected based on the physically sound basis of the retrieval that, with additional development, similar performance can be achieved in other locations to provide continuous spatial and temporal coverage across the Greenland percolation zone. Detecting the subsurface melt during surface freezing is already a significant step for understanding meltwater retention versus runoff in the firm and for tracking subsurface meltwater within the ice sheet hydrology and drainage system, which is important to understand for modeling of ice sheet mass balance and sea level rise.

Data Availability Statement
The SMAP L1CTBE brightness temperature data is available through nsidc.org (https://doi.org/10.5067/XB8K63YM4U8O). The AMSR2 data is available through JAXA data service (https://gportal.jaxa.jp/gpr/), where a free user account has to be created to access the data. The DYE-2 datasets are available in Samimi and Marshall (2020) and the MATLAB code used for the firm modeling is available in a repository in Marshall (2021).

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