Bias in modeled Greenland ice sheet melt revealed by ASCAT

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Abstract. The runoff of surface melt is the primary driver of mass loss over the Greenland Ice Sheet. An accurate representation of surface melt is crucial for understanding the surface mass balance and, ultimately, the ice sheet's total contribution to sea level rise. Regional climate models (RCMs) model ice-sheet-wide melt volume but exhibit large variability in estimates among models, requiring validation with observed melt. Here, we explore novel processing of data from the Advanced SCATterometer

5 (ASCAT) instrument onboard the EUMETSAT Metop satellites, which provides estimates of the spatiotemporal variability of melt extent over the Greenland Ice Sheet. We apply these new maps to pinpoint differences in the melt products from three distinct RCMs, where one is forced at the boundary with two different reanalyses. Using automatic weather station (AWS) air temperature observations, we assess how well RCM-modeled melt volume aligns with in situ temperatures. With this assessment, we establish a threshold for the RCMs to identify how much meltwater is in the models before it is observed at the

10 AWS and ultimately infer the melt extent in the RCMs. We show that applying thresholds, informed by in situ measurements, reduces the differences between ASCAT and RCMs and minimizes the discrepancies between different RCMs. Differences between modeled melt extent and melt extent observed by ASCAT are used to pinpoint (i) biases in the RCMs, which include variability in their albedo schemes, snowfall, turbulent heat fluxes, and temperature as well as differences in radiation schemes, and (ii) limitations of the melt detection by ASCAT, including misclassification in the ablation zone as well as a temporal

15 melt onset bias. Overall we find the RCMs tend to have a later melt onset than ASCAT and an earlier end of melt season with a similar but slightly smaller melt area than identified in ASCAT. Biases, however, vary spatially between models and with compensating errors in different regions, suggesting that one RCM can sometimes represent the present-day surface across the entire ice sheet more effectively than the ensemble mean.

1 Introduction

The Greenland Ice Sheet significantly contributes to the rise in global sea levels, contributing approximately 15 % since the early 1990s (WCRP Global Sea Level Budget Group, 2018). Since 1992, satellite observations have shown that the Greenland Ice Sheet has lost 4892 ± 457 Gt of ice or 13.6 ± 1.3 mm sea level equivalent with half of the mass loss attributed to a decrease in the surface mass balance (SMB) (Otosaka et al., 2023). However, the rate of mass loss has exhibited considerable annual variability in recent years, ranging from 86 ± 75 Gt in 2017 to 444 ± 93 Gt in 2019, with the latter being driven by exceptional surface melting during the summer (Tedesco and Fettweis, 2020). Modeling studies have shown that surface melt on the Greenland Ice Sheet has generally doubled since the 1990s due to a rise in temperature (Tedesco and Fettweis, 2020; van den Broeke et al., 2016). Meanwhile, snow accumulation has remained nearly constant (van den Broeke et al., 2016). In the warm summer months, the surface temperature rises above the melting point of ice, and surface melt occurs. Depending on snow and firn characteristics, meltwater generated at the surface can either collect at the surface and form supraglacial meltwater lakes (Koenig et al., 2015), run off as surface meltwater (Smith et al., 2015) or percolate into the snowpack, where it either refreezes (Forster et al., 2014; Harper et al., 2012) or runs off englacially (Chandler et al., 2013).

At present, regional climate models (RCMs) represent the only approach to obtain comprehensive ice-sheet-wide estimates of meltwater volumes and runoff (Fettweis et al., 2020). However, these models are influenced by the chosen modeling approach, and substantial disparities persist among models (Rae et al., 2012; Vernon et al., 2013; Fettweis et al., 2020). In particular, recent studies suggest that small differences between models at the present day, representing differences in parametrizations, have large effects on projections of melt, runoff and surface mass balance when run into the future, giving greater uncertainty on sea level rise estimates than desirable for climate adaptation purposes (Fettweis et al., 2020). Thus, it is crucial to develop methods to evaluate melt estimates from RCMs against observations of melt to understand these discrepancies and ultimately evaluate which RCMs most realistically model melt (Langen et al., 2017). While automatic weather station (AWS) in situ observations of melt intensity do exist, the sparse distribution over the ice sheet limits the evaluation of melt estimates beyond local scales (Fausto et al., 2018). On the other hand, satellite remote sensing can observe the presence of meltwater at the upper part of the firn pack, while the melt intensity has not yet been measured successfully from remote sensing. Remote sensing satellites provide information on the Greenland Ice Sheet surface melt by observations from the visible to the microwave spectrum, where some of the widely used sensors are Advanced SCATterometer (ASCAT), Sentinel-1, Moderate Resolution Imaging Spectroradiometer (MODIS), and Special Sensor Microwave Imager/Sounder (SSMIS) (Husman et al., 2023). Microwave sensors have the advantage of offering measurements independently of cloud cover, weather conditions, and polar darkness. Over the ice sheets, the backscattering of the microwave signals from snow and ice depends on roughness geometry and electrical properties, which in turn depends on the physical characteristics of the snow and ice (Wismann, 2000; Long, 2017). During the winter, the backscatter signal can exhibit a gradual decrease due to snow accumulation attenuating the volume scattering in the snowpack. As the temperature increases, meltwater at the surface is introduced, and the backscatter signal experiences a substantial drop. This sensitivity to meltwater has enabled several studies to estimate melt over both ice sheets using passive and active microwave measurement with a threshold method to detect the onset of melt and its extent

(Long and Drinkwater, 1994; Wismann, 2000; Ashcraft and Long, 2006; Fettweis et al., 2011; Colosio et al., 2021; Husman
et al., 2023). The magnitude of the decrease in backscatter varies due to factors such as the snow water content and the specific
properties of the snow, such as grain size and the presence of ice layers and lenses, which influence the dielectric properties and
roughness geometries (Wismann, 2000; Long, 2017). Refreezing of meltwater from the previous melt season can percolate into
the firn, leading to the formation of subsurface features such as firn aquifers and ice lenses, which can potentially amplify the
backscatter signal prior to the current melting season (Brangers et al., 2020). Further, subsurface meltwater can still be detected
after refreezing of the surface layer since the low-frequency signals can penetrate moist snow layers. Using a threshold method
proposed by Ashcraft and Long (2006), Husman et al. (2023) showed that the C-band (4–8 GHz) active microwave sensors
detected more melt days than K-band (18-27 GHz) passive microwave sensors in areas with subsurface melt in Antarctica due
to differences in penetration depth. Thus, for a correct identification of surface melt using microwave satellite observations,
it is important to account for penetration depth, changes in dielectric properties, and roughness geometries of the snowpack.
The formation of subsurface ice features and subsurface penetration can lead to significant misclassification of surface melt if
a simple threshold method is used (Ashcraft and Long, 2006; Long, 2017).

Here, we employ a melt detection algorithm that integrates the temporal behavior of the backscatter signal by classifying the
first- and second-time derivatives. Rather than solely identifying the period of meltwater presence, the method distinguishes
between the surface melting and subsequent refreezing of the surface meltwater. However, this method does not estimate the
meltwater volume, meaning we can only use the satellite-observed melt to asses the RCMs' ability to represent the extent of
surface melt realistically. Hence, we compare the melt extent observed by ASCAT to the modeled melt extent by RCMs. To
ensure that the RCM-modeled melt aligns with the in situ observations, we compare modeled melt volume to observed 2m
temperatures at automatic weather stations (AWS) stations to establish the melting threshold (mm of water equivalent per day,
mm w.e. day^{-1}) to identify how much meltwater is in the models before it is observed at the AWS. Once the melt extent is
inferred from the RCMs it's possible to compared with the melt extent observed by ASCAT to identify biases within the RCMs
and limitations in the ASCAT melt observations.

2 Data

2.1 PROMICE AWS

The Programme for Monitoring of the Greenland Ice Sheet & Greenland Climate Network, PROMICE GC-net AWS, offers
hourly and daily meteorological and glaciological in situ measurements for 54 weather stations on the Greenland Ice Sheet,
tundra, and peripheral glaciers (Fausto et al., 2021; How et al., 2022). Here, we include the 34 stations on the Greenland Ice
Sheet. PROMICE GC-net only includes active weather stations, but the historical GC-net data includes several discontinued
stations. Here data from the Summit, GITS, and PertermannELA stations are included, as they overlap in time with ASCAT
data (Steffen et al., 1996, 2022). See Fig. 1 for the location of AWS stations.
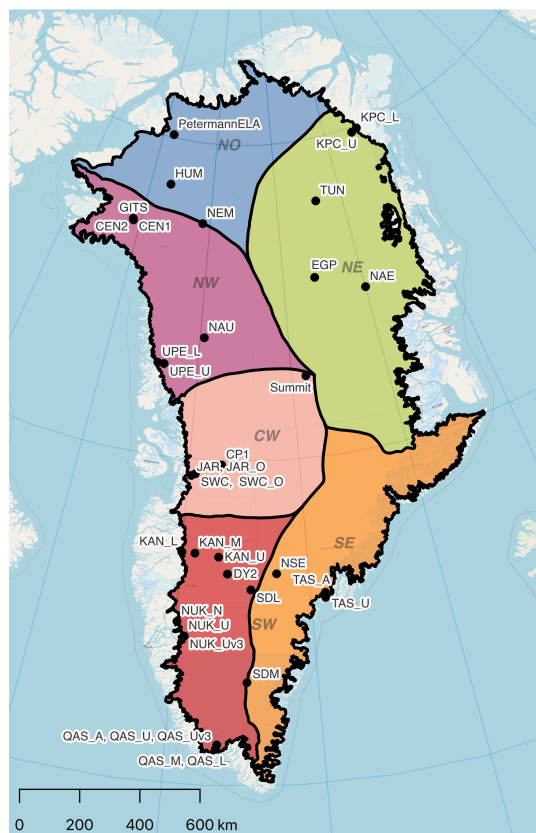
Figure 1. Location of AWS stations included in the study. Only AWS stations on the ice sheet (ASCAT melt detection domain) are included in this study. Further, included are the Rignot and Mouginot (2012) drainage basins that are utilized in the subsequent evaluation of RCMs modeled melt extent against ASCAT observed melt extent.

2.2 Regional climate models

The melt volume from RCMs are derived by closing the surface energy budget. When the skin temperature exceeds 0 °C, additional energy contributes towards melting, resetting the skin temperature to 0 °C (Langen et al., 2015; Noël et al., 2018). However, different choices of parameters such as surface albedo and subsurface schemes impact the surface energy balance simulated within these models and thereby result in the different melt volumes. We compare the melt extent observed by ASCAT with the modeled melt extent from three RCMs: HIRHAM5, RACMO2.3p2, and MARv3.12, see Fig. 2 and Fig. 3. A detailed description of model differences is provided in the following.
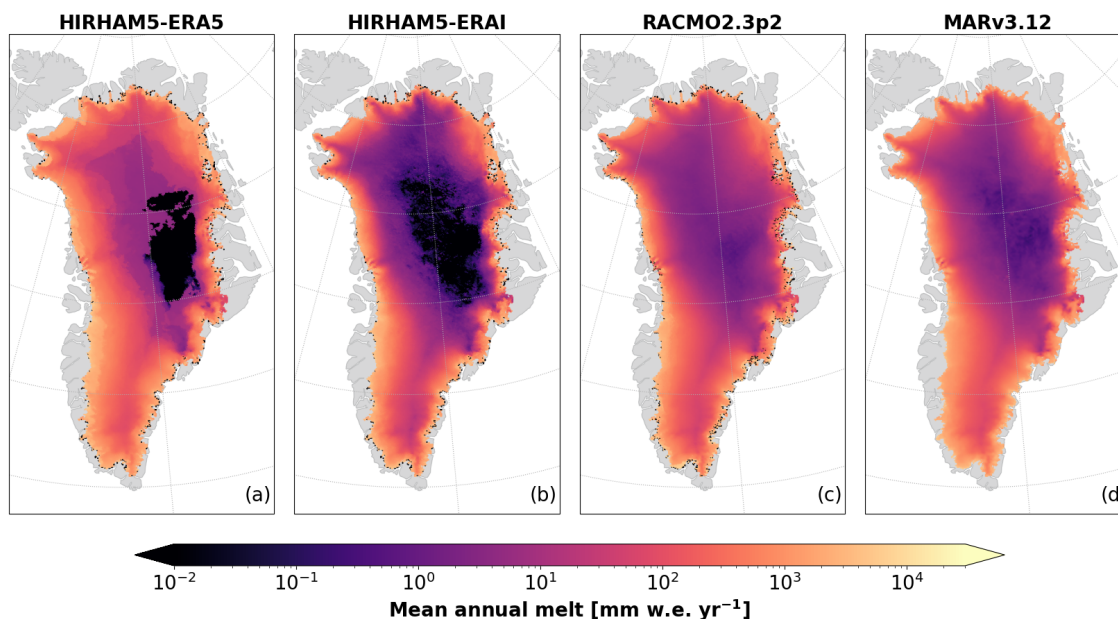
Figure 2. Modeled mean annual melt by different RCMs inside the ASCAT data mask (2007-2020).

HIRHAM5

HIRHAM5 (Lucas-Picher et al., 2012) utilizes a rotated polar grid at $0.05° \times 0.05°$ horizontal resolution, which for the Greenland Ice Sheet corresponds to approximately 5.5 km. HIRHAM5 is developed from the dynamics of the numerical weather forecast model High-Resolution Limited Area Model (HIRLAM, Undén et al. (2002)) combined with the physics from the ECHAM5 general circulation model (Roeckner et al., 2003) to ensure accurate simulation of the surface energy balance. HIRHAM5 is forced on the lateral boundary with 6-hourly global reanalysis temperature, relative humidity, wind vectors, and pressure fields. Further, daily sea ice concentration and sea surface temperature fields are also used to force the model (Langen et al., 2017). Here, we include HIRHAM5 run with both ERA-interim, for the period 1979 - 2019, (Dee et al., 2011) and ERA5, for the period 1960 - 2020, (Hersbach et al., 2020). HIRHAM5 forced with ERA-interim is referred to as HIRHAM5-ERAI and HIRHAM5 forced with ERA5 as HIRHAM5-ERA5. Further, the surface albedo in HIRHAM5-ERAI is derived from MODIS gridded surface albedo (Box et al., 2012), described in (Langen et al., 2017), while the surface albedo in HIRHAM5-ERA5 is computed internally as a linear function of temperature, described in (Langen et al., 2015). The outputs from both HIRHAM5 runs are used to force the offline subsurface model described in Langen et al. (2017). The offline subsurface model includes a multilayer surface snow and mass balance scheme that simulates melt percolation, retention and refreezing with a vertical resolution down to 60 m w.e. (Langen et al., 2017)

RACMO2.3p2

The polar Regional Atmospheric Climate Model (RACMO2.3p2) is run on approximately 5.5 km (0.05° × 0.05°) horizontal resolution (Noël et al., 2018, 2019). ACMO2.3p2 also integrates the numerical weather forecasting dynamics from HIRLAM
110 (Undén et al., 2002) with the physics from the European Centre for Medium-Range Weather Forecasts–Integrated Forecast System cycle CY33r1 (ECMWF, 2009) to accurately simulate the surface energy balance. On the lateral boundary, On the lateral boundary, RACMO2.3p2 uses the same 6-hourly and daily ERA5 fields as HIRHAM5-ERA5 (Hersbach et al., 2020). The snow albedo is derived from snow grain size, cloud optical thickness, solar zenith angle, and impurity concentration in snow. However, to account for temporal variability in the ablation zone, gridded MODIS observations of bare ice (Box et al.,
115 2012) are included in these areas (Van Angelen et al., 2012). . The model includes a multilayer snow module for simulating surface melt partitioning into percolation, retention, refreezing, and ultimately runoff (Ettema et al., 2010). The 5.5 km product is statistically downscaled to a horizontal resolution of 1 km to represent the steep SMB gradients found over narrow glaciers and confined ablation zones at the rugged margins of the ice sheet (Noël et al., 2016).

MARv3.12

120 The *Modèle Atmosphérique Régional*, MARv3.12, is run at a 10 km horizontal grid resolution (Fettweis et al., 2013, 2017; Tedesco and Fettweis, 2020). MARv3.12 combines atmospheric modeling with a Soil Ice Snow Vegetation Atmosphere Transfer Scheme (SISVATS) (Gallée and Schayes, 1994) to simulate the surface energy balance and mass balance processes over the ice sheet. The MARv3.12 is forced at the lateral boundaries with ERA5 (Hersbach et al., 2020) at 6-hourly temporal resolution. Output values are averaged to obtain daily values (Tedesco and Fettweis, 2020). MARv3.12 includes a snow model that
125 simulates a number of layers of snow, ice, or firn of variable thickness and energy- and mass-transports between each layer. The snow model also provides snow grain properties, which are used to simulate snow albedo (Antwerpen et al., 2022).

2.3 ASCAT melt maps

The ASCAT instrument onboard the EUMETSAT MetOp polar-orbiting satellites provides measurements since 2007. ASCAT is a Real Aperture Radar (RAR) instrument and measures radar backscatter in vertical polarization at a range of incidence angles
130 from 25°to 65°at a frequency of 5.255 GHz (C-band) (Figa-Saldaña et al., 2002; Long, 2017). With a spatial resolution of 25 km, ASCAT had limited land applications, but with the introduction of the scatterometer image reconstruction (SIR) algorithm, the utility of ASCAT data has significantly improved (Lindsley and Long, 2010). The SIR algorithm takes advantage of image reconstruction techniques and the spatial overlap of measurements over a region to enhance the effective spatial resolution over a time interval. SIR depends on the number of measurements where increasing the number of measurements leads to a reduction
135 of noise and improvement of the spatial resolution. However, the radar characteristics must remain constant between passes during the interval time. We refer to Long et al. (1993) and Long and Drinkwater (1994) for a more detailed description of the SIR algorithm. For Greenland, a 4-day time interval is appropriate as it ensures sufficiently dense sampling while justifying the assumption of constant radar characteristics (Lindsley and Long, 2010). With the 4-day time interval, the effective resolution

of the ASCAT SIR product becomes 4.45 km. As the time interval increases, abrupt changes and short-term variability in the
140   backscatter signal are less pronounced. Consequently, the resolution-enhanced ASCAT product may not capture short melt
events in the spring and intense precipitation events, as these signals are averaged (Long and Drinkwater, 1994; Lindsley and
Long, 2010).

The ASCAT backscatter time series provided by the SIR product is used here to identify four different melt stages by
applying a hierarchical decision tree using dynamic thresholds based on the previous winter reference months (JFM) and the
145   first and second the first- and second-time derivatives of the backscattered signal, σ^0 (Nagler et al., 2024). During the winter
months the backscatter signal is relatively stable and only minor variations may occur due to changes in snowpack properties
(label Stage-1 (ST-1), no melt). As the snow surface starts to melt in spring, rising above liquid water content of $\sim 1\%$ volume
(Mätzler, 1987), the backscatter signal decreases significantly. This rapid drop in the backscatter coefficient is utilised to
identify the onset and occurrence of surface melt (label ST-2A, surface melt). At intense melt events, the backscatter signal
150   becomes fully saturated, and an increase in the melt intensity does not lead to further lowering of the backscatter signal (label
ST-2B, wet snow layer). As the meltwater starts to refreeze, the backscatter signal will gradually increase again, returning to
the stable winter conditions once the melt water down to the radar penetration depth is refrozen (label ST-3, increase in the
refrozen layer). For a more detailed description of the melt stage classification we refer to (Nagler et al., 2024).

As an example, Fig. 4a, shows the backscatter measurements and the melt classification are shown for the KAN_U AWS.
155   The winter dry signal changes after at least one melt season, highlighting the melt classification method's ability to correctly
detect melt despite a difference in the winter signal before and after the melt season. When comparing the melt extent observed
by ASCAT and the melt extent model by the RCMs, we excluded label ST-3 (increase in the refrozen layer) since we are only
interested in comparing surface melt. Figure 4b illustrates a snapshot of the melt detection and classification from 07-08-2017.
Refreezing or no melting is observed in pixels close to the ice sheet margin when melt occurs at higher elevations on the ice
160   sheet. Further, when looking at the mean annual number of melt days, the lower ablation zone exhibits fewer melt days than
at higher elevations. This seemingly incorrect classification of melt near the ice margin is a effect of changes in the surface
roughness associated with melt. Changes in surface roughness can counteract the decrease in backscatter associated with melt,
effectively concealing melt in the backscatter signal. Therefore, when comparing melt extent with RCMs, we mask out these
areas by applying the maximum elevation of the snowline between 2007-2020 (Box et al., 2012), where pixels with an elevation
165   below are excluded in the comparison (Fig. 4d).

3   Methods

Modeled surface melt in RCMs is subject to large variability among models as seen in Fig. 2 and discussed in e.g Fettweis
et al. (2020). The Greenland Ice Sheet SMB model intercomparison project (GrSMBMIP) suggested that discrepancies between
RCMs are not systematic (Fettweis et al., 2020), thus there is a need for individual evaluation of each modeled melt volume
170   product before we can compare the extent observed by ASCAT. We compare the RCM output of surface melt with observed 2 m
temperature data from PROMICE GC-net AWSs to identify and quantify temperature biases in each of the RCMs. Furthermore,

we can use this approach to establish a threshold (in mm w.e. day^{-1}) to identify how much meltwater must be in the models before we can also observe it at the AWS. Since the AWS measurements are significantly affected by local scale weather conditions, this approach only ensures that the modeled melt by the RCMs aligns primarily at these specific locations.

Air temperature is strongly correlated with melt since melt is a response to a positive surface energy balance, which occurs when the surface temperature is greater than 0 °C (Cuffey and Paterson, 2010). However, the local properties of the snowpack can also affect when melt occurs, and melt can occur in the snowpack when air temperatures are below 0 °C. Thus, it is crucial to consider that the heat content of the overlying atmosphere is not the sole driver of melt when we compare the modeled melt volume against the days with observed melt as indicated by AWS temperature measurements. With this approach, we apply a threshold to identify days with significant melt in the RCMs but also implement a threshold for the temperature observations to identify when melt occurs in the snowpack at the AWS. We explore various thresholds for temperature observations to account for other variations of the snowpack influencing the melting point.

A logical measure to identify how well the models and in situ observations align most closely would be to maximize the number of days where both the models and in situ observations agree on either melting or no melting. However, since the number of days with melt is fewer than those without melt, the dataset exhibits an imbalance. In the ablation zone, the imbalance is less pronounced with prolonged periods of melt in the summer, whereas in the accumulation zone, melt occurs for shorter periods. This data imbalance means that many days with agreement between RCMs and AWS can be attributed to seasonal patterns, concealing disagreement in the melt season. Instead, we utilize the receiver operating characteristic (ROC-) curve (Peterson et al., 1954) and the precision-recall (PR-) curve (Davis and Goadrich, 2006) to provide a more nuanced understanding of the alignment between RCMs and AWS. Given that TP is the number of true positives, TN is the number of true negatives, FP is the number of false positives, and FN is the number of false negatives, the ROC curve is a measure of the ability to distinguish between two classes across all thresholds and consists of a graph that shows the true positive rate $\left(TPR = \frac{TP}{TP+FN}\right)$ versus the false positive rate $\left(FPR = 1 - \frac{TN}{TN-FP}\right)$. The ROC curve provides the total performance measure across all potential classification thresholds where a random model will produce a diagonal line. In contrast, a perfect model will have a ROC curve composed of the left and upper boundary lines. The goal is to choose a melting threshold that maximizes the TPR positives while minimizing the FPR. However, in an imbalanced data set, it is possible to produce a good ROC curve by making a large number of FP predictions, especially when the positive class is rare. Thus, for an imbalanced data set, it is important also to consider the PR curve, which is the fraction of TP among the positive predictions $\left(Precision = \frac{TP}{TP+FP}\right)$ versus the TP among the actual positives $\left(Recall = \frac{TP}{TP+FN}\right)$. When evaluating what melting threshold to apply to each RCM, we are looking for the RCM melting thresholds and AWS temperature threshold that maximizes the TPR positives while minimizing the FPR and maximizing the precision and recall.

Figure 5 shows the ROC-curves and PR-curves for possible RCM melting thresholds using different AWS temperature thresholds. The black dot indicates the optimal melting threshold for each RCM (Table 1). For HIRHAM5-ERA5 and HIRHAM5-ERAI, we see that both the best ROC-curve and best PR-curve match, although suggesting very different melting thresholds. The ROC-curve for MARv3.12 and RACMO2.3p2 suggest using temperature thresholds between -0.5 to 1 °C to find the best RCM melting threshold, but looking at the PR-curve the lower temperature threshold results in a worse PR-curve. From

Table 1. Melting thresholds for the different RCMs based on in situ PROMICE AWS observations of 2m temperature and mean air temperature for August and July simulated by the RCMs at AWS stations and observed by the AWS stations using a lapse rate correction. The table showcases the mean air temperatures at six selected AWS and a mean across all stations. Figure 3a-d illustrates the mean JJA air temperature across the Greenland Ice Sheet for each RCMs.

		Mean air temperature [°C]						
	Thresholds [mm w.e. day^{-1}]	CP1	DY2	KAN_U	KPC_U	NUK_U	SDL	All AWS
HIRHAM5-ERA5	4.1	-6.36	-6.78	-5.08	-1.13	0.74	-9.62	-4.02
HIRHAM5-ERAI	0.4	-3.92	-4.04	-2.53	0.29	1.12	-6.50	-2.35
RACMO2.3p2	0.7	-4.66	-4.83	-2.95	-0.80	2.03	-7.14	-1.87
MARv3.12	1.0	-5.16	-5.14	-3.31	-0.93	1.24	-7.71	-2.64
PROMICE GC-net	–	-4.96	-4.70	-3.31	-0.85	-0.84	-6.80	-3.39

the PR-curve, a temperature threshold between -1.0 to -2.0 °C gives better results when choosing the melting thresholds for MARv3.12 and RACMO2.3p2. The mean air temperature for July and August observed by AWS and modeled by the RCMs at the AWS stations suggests a cold bias in HIRHAM5-ERA5, whereas MARv3.12 and HIRHAM5-ERAI have a warm bias. However, the mean air temperature at selected stations highlights that the temperature bias is not systematic across the ice sheet.

4 Results

To evaluate the difference between the mean annual number of melt days in ASCAT and each RCM, we compute the RMSE for the whole ice sheet and each drainage basins (Rignot and Mouginot, 2012). Besides applying the in situ informed thresholds found in Tabel 1, we also apply a baseline threshold of 0.1 mm w.e. day^{-1} to evaluate the number of modeled melt days when biases are not considered. The baseline threshold was set to the smallest value possible without allowing regridding biases to impact the number of melt days. The RMSE between ASCAT and RCMs are showcased in Table 2, where we see that applying the in situ informed threshold improves the discrepancies between modeled melt and ASCAT, except for HIRHAM5-ERAI. RACMO2.3p2 and MARv3.12 show the biggest improvement, although the improvement is not evenly distributed between drainage basins. Since the in situ informed thresholds generally reduce the differences between RCMs and ASCAT compared to the baseline threshold of 0.1 mm w.e. day^{-1} (Table 2), we apply only the in situ informed thresholds in the following. A detailed comparison of the number of melt days using the baseline threshold is provided in Appendix A, showing larger discrepancies between ASCAT and RCMs, corresponding with findings in Table 2.

Figure 6 shows the spatial variability of the number of melt days both within each RCM (upper panel) and in comparison with ASCAT (lower panel). Looking at the spatial variability of the annual number of melt days for the RCMs and ASCAT (Fig. 4c), areas with >100 days of melt lie near the lower ablation zone, but the extent of areas with >100 days of melt varies

Table 2. RMSE of the mean annual number of melt days modeled by RCMs using a uniform threshold and in situ informed thresholds and ASCAT across the whole ice sheet and for each Rignot and Mouginot (2012) drainage basins. RMSE is only computed inside the snowline data mask to mask out areas where ASCAT cannot detect melt; see Fig. 1.

	HIRHAM5-ERA5		HIRHAM5-ERAI		RACMO2.3p2		MARv3.12	
Threshold	0.1	4.1	0.1	0.4	0.1	0.7	0.1	1.0
Full ice sheet	10.70	7.67	7.39	7.76	28.77	6.27	17.78	4.93
NW	8.23	5.13	3.17	3.44	1.97	1.77	3.12	2.00
CW	9.01	5.80	3.30	3.74	2.10	2.10	3.11	2.65
SW	6.88	5.40	6.10	6.69	12.14	4.87	9.68	3.73
SE	5.65	4.89	5.91	6.07	31.56	5.78	18.75	4.08
NE	4.53	3.17	3.13	3.08	2.94	2.15	3.21	1.93
NO	5.11	3.35	2.49	2.68	1.56	1.38	1.66	1.76

from ASCAT and among models. Most noticeable is HIRHAM5-ERA5, which has substantially larger areas with >120 days of melt. Areas with <1 day of melt on average are shown in white in Fig. 6, illustrating areas where melt very rarely occurs. Again, there is large variability among models in terms of modeling areas with almost no melt days.

230   While Table 2 illustrates the variability in error between ASCAT and RCMs across drainage basins, the lower panels in Fig. 6 reveal that the largest differences are concentrated near the ice margin across all basins. Generally, the SW and SE basins have the highest RMSE, explained by relatively large areas with 20 or more days of difference in these basins (Fig. 6. Similarly, HIRHAM5-ERA5 exhibits a high RMSE in the western basins, corresponding with large areas where HIRHAM-ERA5 models 20 or more melt days compared to what ASCAT observes. Although the in situ informed threshold reduces the differences,

235 HIRHAM5-ERA5 continues to produce more melt days than ASCAT or any other model, even when the melting threshold is vastly greater than the other RCMs. On the other hand, HIRHAM5-ERAI consistently underestimates the number of melt days across all drainage basins. MARv3.12 and RACMO2p2.3 show similar patterns of variability, where only large differences to ASCAT occur close to the maximum snowline elevation.

     Results from all RCMs and ASCAT (Fig. 7a) indicate that, on average, the melting season begins at the beginning of May

240 and culminates around July when the greatest melt extent occurs. While RCMs suggest that the melt season on average ends around mid-September, small melt areas are still observed in ASCAT well into October. The average maximum melt extent is approximately 30 % of the ice sheet, except for HIRHAM5-ERA5 with >35 %. At the beginning of the melt season, ASCAT detects the increase in melt extent earlier compared to RCMs, but the decrease in melt extent at the end of the melt season corresponds well with the models. In August and at the beginning of September, the melt extent decreases but with small

245 periodical increases, which ASCAT also detects prematurely, although not as pronounced as at the beginning of the melt season.

In 2012, an extreme melting event was observed across almost the entire ice sheet (Nghiem et al., 2012). We can use this year to showcase how well an extreme but relatively short melt event is captured in the RCMs and by ASCAT. Results show that using the in situ informed thresholds, only RACMO2p2.3 predicts melting of >90% of the ice sheet, but the rest only predict approximately 80% (Fig. 7b). Figure 7b also shows that melt is detected earlier by ASCAT at the start of the season. During the increase in melt extent in end-July to mid-August ASCAT was able to capture an increase in melt extent, but the magnitude of the increase was smaller compared to the models.

5 Discussion

The goal of this study is to use ASCAT to understand how RCMs model ice-sheet-wide melt extent compared to observations and further pinpoint biases within models leading to the observed discrepancies. By comparing RCM with PROMICE GC-net temperature observations, we are able to determine how well the RCMs align with in situ observations. While the uneven distribution of AWS stations, with a concentration in the ablation zone, may result in certain areas being better represented in the assessment than regions with fewer AWS stations, Tab. 2 shows that by ensuring that the RCMs align with in situ measurements at specific locations, the modeled melt extent and satellite observed melt extent show better agreement. Further, with this approach, we identify that HIRHAM5-ERA5 shows large discrepancies from PROMICE GC-net air temperature observations. The melt threshold in HIRHAM5-ERA5 is considerably higher than the remaining melt estimates. The identified melting threshold of 4.1 mm w.e. day^{-1} suggests potential issues with the representation of melt in HIRHAM5 when forced with ERA5. Consequently, this highlights the importance of carefully considering model performance. When we compare the number of melt days in the RCMs versus those observed by ASCAT, MARv3.12 has the lowest RMSE for the whole ice sheet. However, MARv3.12 performs predominantly better on the eastern side of the ice sheet, whereas RACMO2p2.3 performs better on the west coast and in the northernmost areas. While none of the RCMs exhibits perfect agreement with either PROMICE GC-net or ASCAT observations when looking at the RMSE and the spatial differences between the annual number of melt days, neither MARv3.12 nor RACMO2p2.3 has an advantage over the other. On the other hand, HIRHAM5-ERA5 and HIRHAM5-ERAI display considerable discrepancies in terms of number of melt days when compared to ASCAT, each displaying unique patterns of deviation. Our analysis shows the value in using common independent spatially and temporally varying datasets to evaluate and improve models and we suggest that this ASCAT dataset is a useful addition to better understand biases in models, especially as it is independent of other datasets such as MODIS that have been used to develop models.

5.1 Biases in RCMs

Utilizing in situ observations to assess biases and to determine an appropriate threshold for the melt extent in RCMs, we reduce overall inter-model discrepancies as well as differences in melt extent compared to that observed by ASCAT. Despite applying the in situ informed thresholds, persistent patterns between RCMs and ASCAT remain. HIRHAM5-ERA5 is the only model that, on average, predicts more melt days than ASCAT while also having a substantially higher melting threshold compared to the other RCMs melt outputs. HIRHAM5-ERAI, RACMO2.3p2, and MARv3.12 all model fewer melt days than

ASCAT on average in the lower accumulation zone, indicating a limitation in the observation of melt by ASCAT. However, the
magnitude of disagreement between RCM and ASCAT varies from RCM to RCM and region to region (Table 2), suggesting
that the melt extent in these areas is most likely not well represented either in the RCMs, or that the melt threshold should
be considered non-stationary according to local conditions. While HIRHAM-ERA5 exhibits the largest meltwater production
(Fig. 2), HIRHAM-ERA5 is also characterized by the lowest mean JJA air temperatures (Fig. 3a-d). In general, HIRHAM-
ERA5, MARv3.12 and RACMO2.3p2, all forced with the ERA5 reanalysis, tend to report lower air temperatures compared to
HIRHAM5-ERAI. This trend is likely originating from ERA5 exhibiting lower air temperatures than its predecessor, ERAI, as
highlighted by (Krebs-Kanzow et al., 2023). While some variability among the models forced with ERA5 exists, the models
commonly exhibit a higher mean JJA downward shortwave radiation at the surface (SWD) compared to HIRHAM-ERAI.
Krebs-Kanzow et al. (2023) similarly reported an overestimation of SWD in ERA5 compared to ERAI. Since the differences
in air temperature and SWD between ERA5 and ERAI have implications for meltwater production and ultimately runoff,
Krebs-Kanzow et al. (2023) concluded that replacing ERAI with ERA5 forcing in an energy balance model of the Greenland
Ice Sheet requires some recalibration to reproduce existing observations. In this study, we show the implications on meltwater
production and extent when forcing the HIRHAM5 SMB model with ERA5 instead of ERAI without recalibration, though the
inclusion of a different albedo scheme is likely to be more important.

In addition to the distinct forcing fields in the two HIRHAM5 outputs, the approach for determining surface albedo dif-
fers. The simple surface albedo scheme in HIRHAM-ERA5 results in a lower mean JJA surface albedo in the ablation zone
and lower accumulation zone compared to HIRHAM-ERAI, which included MODIS observations in the surface albedo
scheme (Fig. 3e and 3f). RACMO2.3p2 is characterized by the lowest surface albedo across the entire ice sheet, while
MARv3.12 and HIRHAM5-ERAI are dominated by lower surface albedo, especially in the accumulation zone. Surprisingly,
while RACMO2.3p2 and HIRHAM5-ERAI both report to incorporate MODIS bare ice albedo observations in the surface
albedo computation in the ablation zone, the resulting surface albedo differs greatly between models. In the RCMs, the surface
albedo is a crucial parameter for simulating the surface energy balance, contributing to a higher surface energy balance when
the surface albedo is low. A low albedo in the ablation zone and lower accumulation will increase the meltwater production in
these areas. Due to high variability of air temperature, SWD, and surface albedo among models, the albedo parametrization and
radiation and temperature schemes within models should be critically assessed using high quality measurements to reduce the
observed discrepancies in the models' estimates of meltwater production (Fig. 2). By aligning model parameters more closely
with observational data, we can improve the model estimates of meltwater production and ultimately runoff.

5.2 Limitations of ASCAT melt observations

We use the maximum extent of the snow line to mask out the ablation zone when comparing the RCMs to ASCAT due to
nonphysical observations of refreezing by ASCAT in these areas (Fig. 6). This is not only due to biases in the melt classification
algorithm but also comes from the microwave data itself. Although melt causes a drop in the backscatter signal, processes
other than the refreezing of liquid water can counteract the decrease in the backscatter signal. Once the surface starts to melt,
the surface roughness changes, which can cause an increase in the backscatter signal, potentially concealing the melt in the

backscatter signal. Since the effect of changing surface roughness on the backscatter signal is not fully understood, it is difficult to remove this bias in melt detection other than removing areas where changes in surface roughness are very pronounced. We further see this systematic misclassification of refreeze or no melting in ASCAT when investigating the 2012 melt season, where ASCAT in the late melt season detects a lower melt extent compared to RCMs. Since the retrieved refreezing from ASCAT is not included in the melt season, misclassifications that stem from melting being misclassified as refreezing due to change in the surface roughness are not included, potentially contributing to a smaller melt extent at the end of the melt season.

Detectable in both the 2012 melt season and the annual mean cycle of melt extent, ASCAT detects the increase of melt extent before the RCMs, partly explained by the preprocessing averaging done to enhance the spatial resolution. Although most pronounced at the beginning of the season, we see that the earlier melt detection also occurs when there's an increase in the melt extent in the late season. On average, the magnitude of the melt seasonal cycle of melt extent agrees well with RCMs, suggesting that melt is classified prematurely but not incorrectly.

6   Conclusions

ASCAT provides a valuable tool for evaluating the performance of RCMs, which is currently the only source for assessing the melt volume on a global scale of the ice sheet. By utilizing observations of melt extent by ASCAT, we can evaluate how well four different RCMs melt outputs represent melt spatially and temporally across the Greenland ice sheet at the present day. To ensure that the RCM-modeled melt aligns well with in situ observations, we compare the RCMs melt output at PROMICE GC-net AWS. Assuming a strong correlation between 2m air temperature and melting, we can use PROMICE air temperature measurements to assess temperature biases and determine a melting threshold in the RCMs to identify days with significant melt. Here, we find that HIRHAM5 forced with ERA5 shows potential issues with the representation of melt due to its relatively poor alignment with PROMICE air temperature measurements. HIRHAM5 forced with ERA-Interim, MARv3.12, and RACMO2p2.3 all show similar alignment with PROMICE, but when comparing with ASCAT melt extent, MARv3.12 and RACMO2p2.3 show better agreement with ASCAT, but each RCM shows distinct patterns of variations. This suggests that in some cases one RCM can represent present-day melt extent across the entire ice sheet more effectively than the ensemble mean, as variability among models does not appear to be random variations.

The variability among modeled JJA air temperature, SWD, and surface albedo can explain the large discrepancies among modeled meltwater production (Fig. 2). Notably, we show the implications for meltwater production when running the HIRHAM5 SMB model using ERA5 instead of ERAI without any recalibration. Further, we show that incorporating MODIS bare ice into the surface albedo scheme can lead to more accurate simulations of surface energy balance and, consequently, meltwater production. Despite both RACMO2.3p3 and HIRHAM5-ERAI using similar MODIS bare ice observations and having similar dynamical schemes, the surface albedo and its effects on meltwater production varied substantially between models, highlighting the need for a critical evaluation of model outputs against high-quality measurements to reduce inter-model discrepancies. In general, our analysis shows the value in using common independent datasets such as ASCAT to evaluate and improve models as it is a useful addition to better understand biases in models.

Code availability. Code is publicly available at https://github.com/anpug/4DG_meltmaps.git

Data availability. ASCAT melt maps are available at https://cryoportal.enveo.at/data/ under meltmaps. PROMICE GC-Net AWS 2m air temperature are available on GEUS Dataverse (https://doi.org/10.22008/FK2/IW73UU, How et al. (2022)). Further, historical GC-net 2m air temperature data is available on GEUS Dataverse (https://doi.org/10.22008/FK2/VVXGUT, Steffen et al. (2022)). HIRHAM5 forced with
350   ERA-Interrim is available at https://ensemblesrt3.dmi.dk/data/prudence/temp/nichan/Daily2D_GrIS/ (Langen et al., 2017) and HIRHAM5 forced with ERA5 will be made availble once the paper is published https://doi.org/10.11583/DTU.25568040 . RACMO3.2p2 is freely available upon request (Noël et al., 2019). MARv3.12 is available at ftp.climato.be/fettweis/MARv3.12/Greenland (accessed May 2023, (Tedesco and Fettweis, 2020))

Appendix A: Comparison between RCMs and ASCAT using the baseline threshold of 0.1 mm w.e. day^{-1}
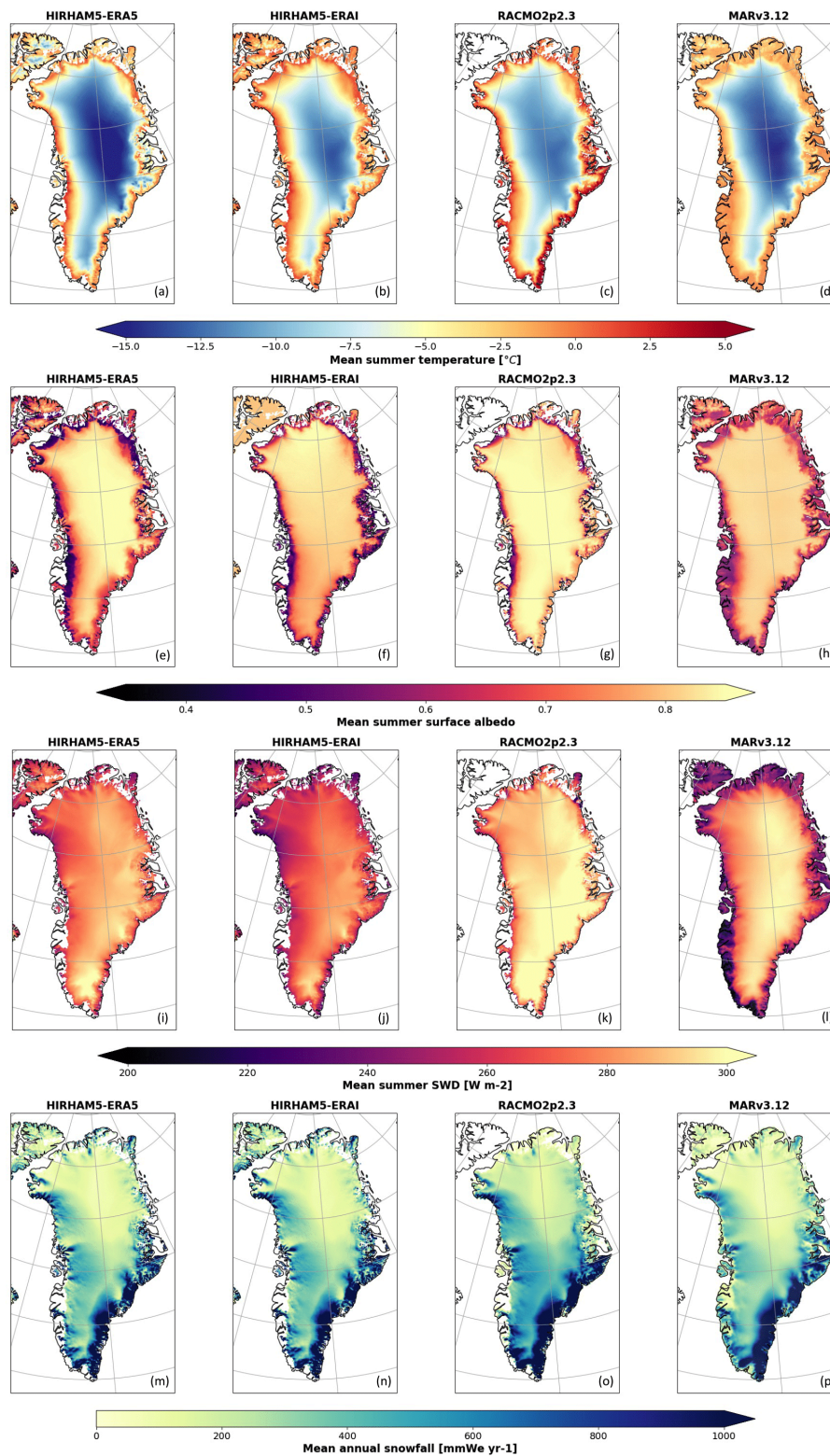
Figure 3. RCM simulated varibles from 2007-2020 for HIRHAM-ERA5, HIRHAM-ERAI, MARv3.12 and RACMO2.3p2. (a-d): mean JJA

temperatures in °C, (e-f): the JJA surface albedo, (i-l): the JJA SWD in W m-2, and (m-p): the mean annual snowfall in mm w.e. yr^{-1}.
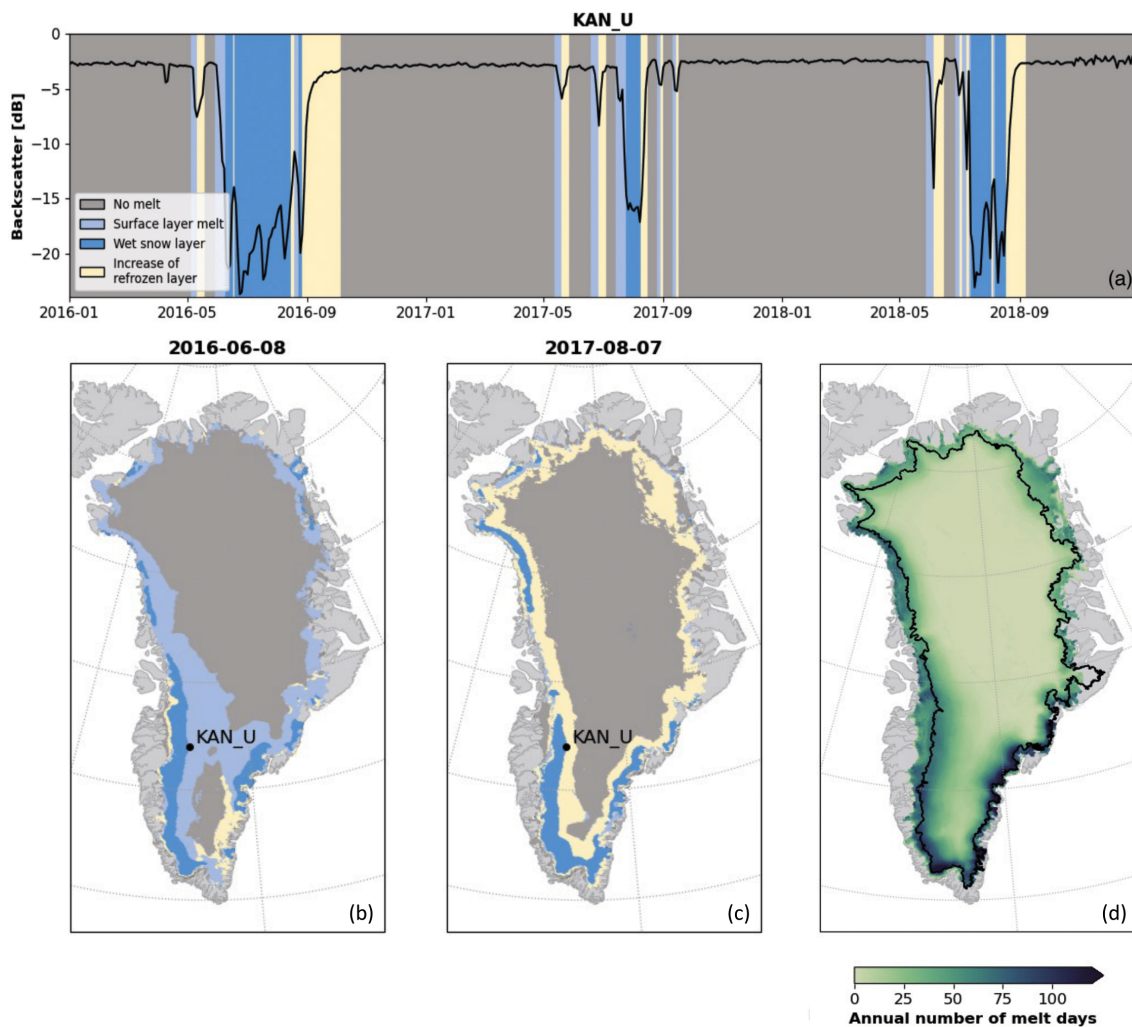
Figure 4. (a) 2016-2018 melt detection and the backscatter signal at KAN_U. (b-c) Two examples of the spatial distribution of melt detection on the 8th of June 2016 and 7th of August 2017. (d) Mean annual number of melt days. In (d) we apply the maximum elevation of the snowline between 2007-2020 (black line) to mask out areas where ASCAT persistently cannot correctly detect the presence of liquid water.
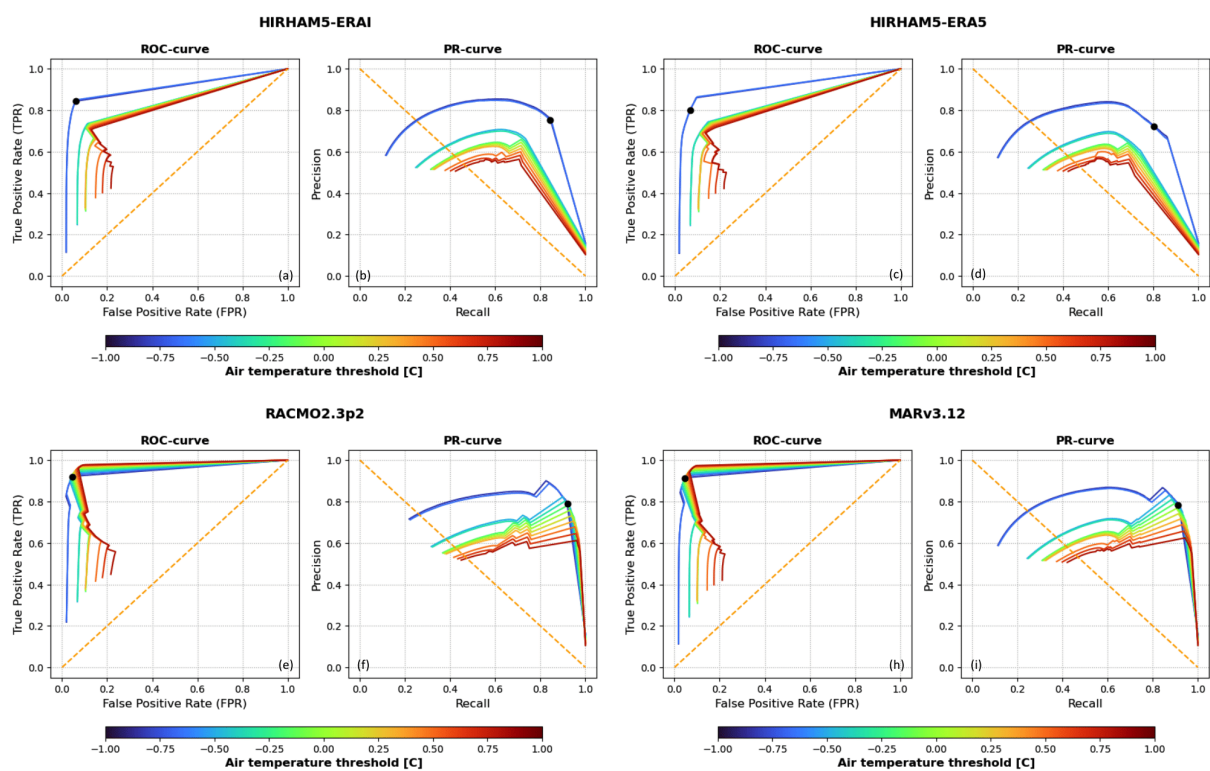
Figure 5. ROC- and PR-curves for possible RCM melting thresholds using varing AWS temperature thresholds. The black dot indicates the optimal melting threshold for each RCM given in Table 1.
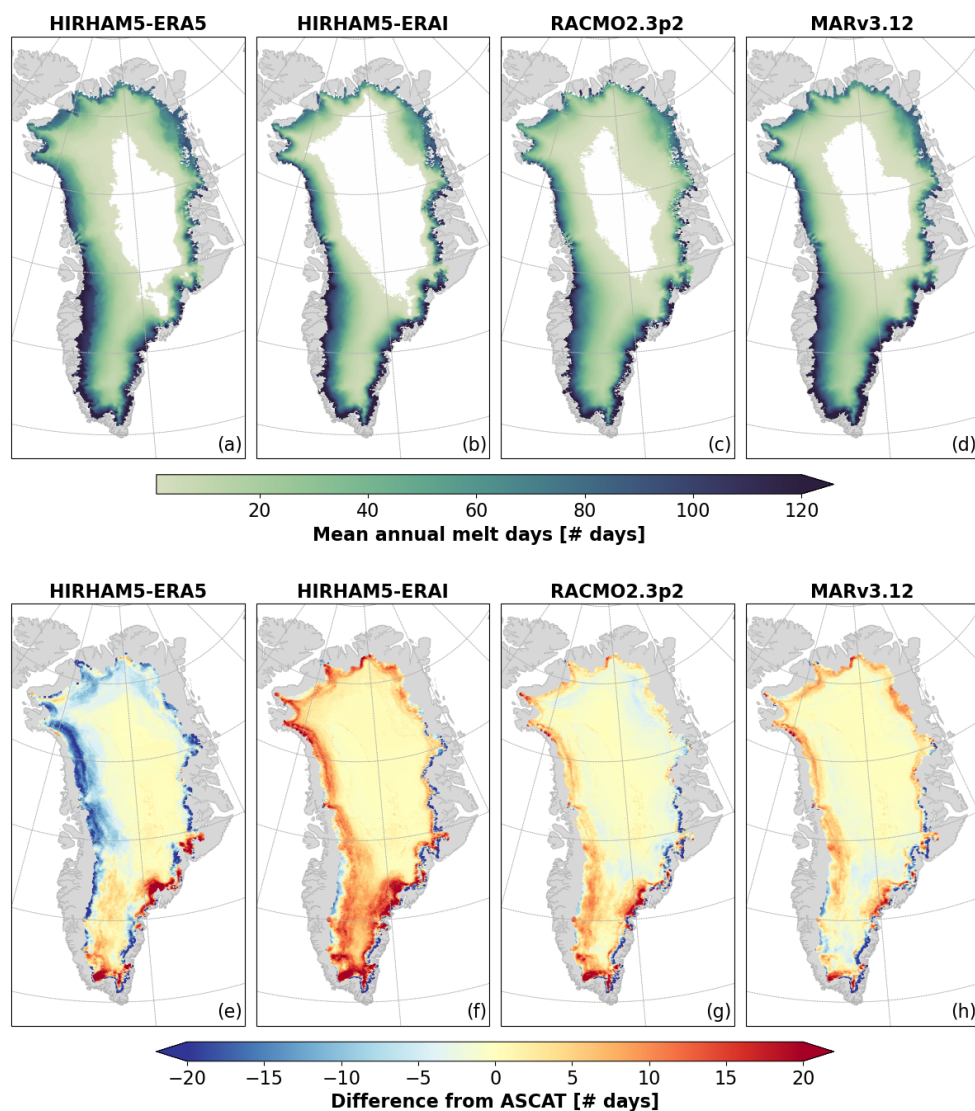
Figure 6. (a-d): The mean annual number of melt days modeled by the RCMs using an in situ informed melt threshold to defined days with significant melt. Pixels with <1 day of melt on average are marked as white, showcasing areas where melt rarely occurs. (e-h) The mean annual difference between the number of melt days in ASCAT and RCMs areas above the 2007-2020 maximum snowline elevation (Fig. 4d). Red areas correspond to more melt days in ASCAT on average and blue areas correspond to more melt days in the RCM on average. Melt in ASCAT is defined as Label ST-2A and ST-2B.
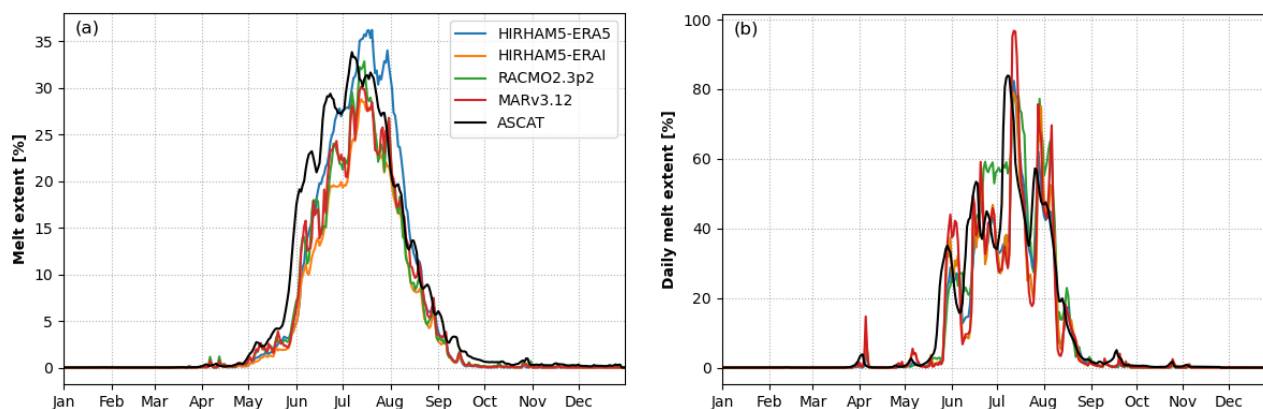
Figure 7. (a) Mean seasonal melt extent [%] modeled by RCMs using in situ informed thresholds and retrieved from ASCAT (2007-2020). In situ informed thresholds are given in Table 2. (b) Daily melt extent [%] modeled by RCMs using in situ informed thresholds and retrieved from ASCAT in 2012. In situ informed thresholds are given in Table 2.
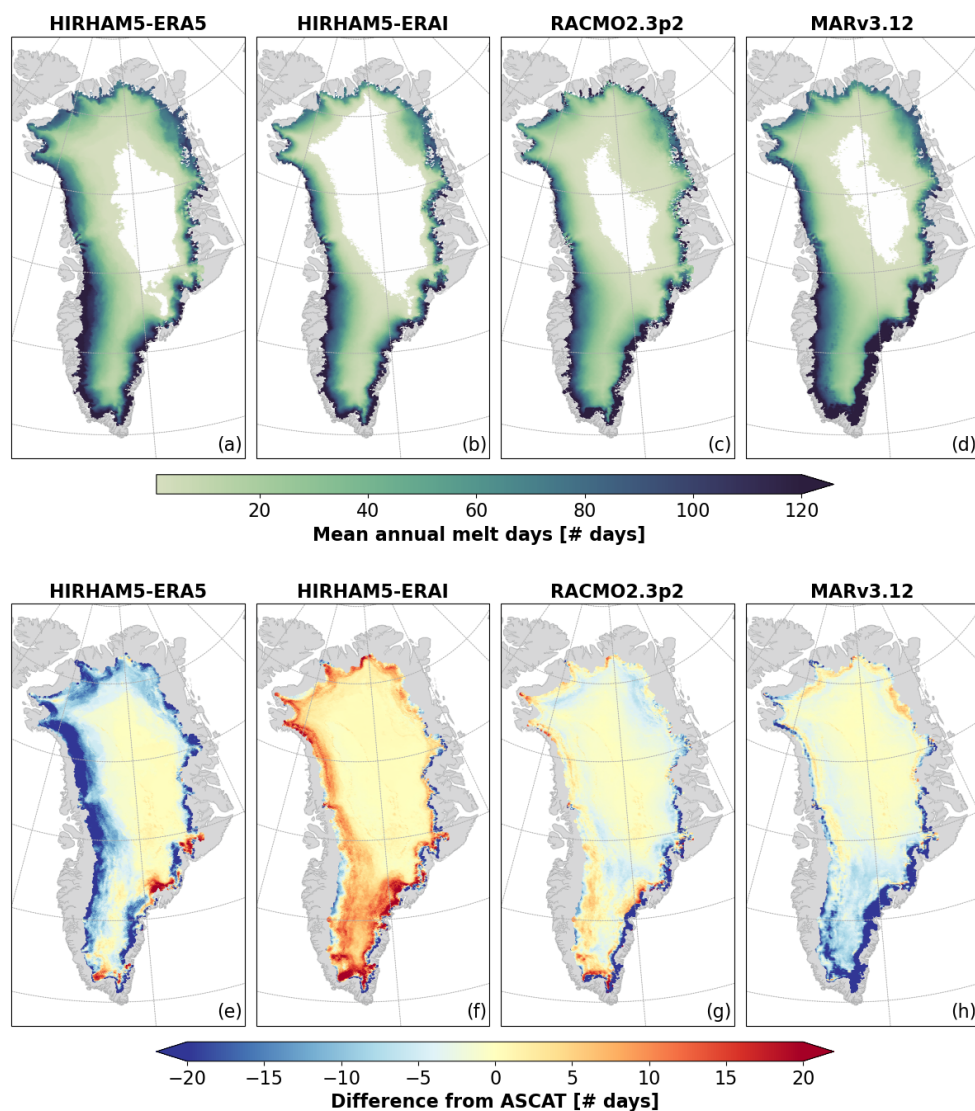
Figure A1. (a-d): The mean annual number of melt days modeled by the RCMs using an in situ informed melt threshold to defined days with significant melt. Pixels with <1 day of melt on average are marked as white, showcasing areas where melt rarely occurs. (e-h) The mean annual difference between the number of melt days in ASCAT and RCMs areas above the 2007-2020 maximum snowline elevation (Fig. 4d). Red areas correspond to more melt days in ASCAT on average and blue areas correspond to more melt days in the RCM on average. Melt in ASCAT is defined as Label ST-2A and ST-2B.

355 *Author contributions.* AS and LSS framed the original study, AP further developed this and wrote the first draft of the paper with the help of AS, NH, LSS, RM, and SBS. TN, SS, and JW developed the presented ASCAT classification algorithm and provided support for the data analysis and discussion. NH processed and provided the HIMHAM5 data. All authors have revised the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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