Authors' response to reviewer #1 of the manuscript "Exploring new EarthCARE observations for evaluating Greenland clouds in RACMO2.4" by Thirza N. Feenstra et al., Atmospheric Measurement Techniques (AMT): egusphere-2025-5623

We would like to thank reviewer #1 for taking the time to review our manuscript. The provided comments and suggestions are addressed below and will definitely help improve the manuscript. Responses to the individual comments are shown in red, and changes we are planning to make in the manuscript are shown in blue.

General comments

It is well known that a polar regional climate model is a valuable tool for estimating the surface mass balance of the polar ice sheets, which governs ice sheet mass balance and, in turn, global sea level. Therefore, it is necessary to continue developing such a polar regional climate model to provide more reliable climate information on snow/ice accumulation/ablation over polar ice sheets. In this study, the authors focus on the Arctic region around Greenland and compare the polar regional climate model RACMO (version 2.4p1), widely recognized in the global cryosphere community as a reliable model, with EarthCARE observations of cloud microphysics. As stated in this paper, the authors plan to improve RACMO's overall performance by leveraging the knowledge gained from such comparisons. This is undoubtedly a novel challenge that has not been conducted in the global cryosphere community. In this paper, only two case studies are presented because EarthCARE observations are available only from May 2024; however, I believe this study has the potential to serve as a future benchmark for the polar regional climate modeling community. In this respect, this paper fits well with the scope of the special issue (SI) entitled "Early results from EarthCARE". This manuscript is generally well written and easy to follow. Therefore, I suggest that this paper can be considered for publication in this SI once the authors address the following points.

Specific comments (major)

L. 124: What do the authors mean by "radiative effects of clouds" calculated by the McICA (Monte Carlo Independent Column Approximation) method here? Do the authors mean heating rates by clouds? Or the contemporary clear-sky downward radiation? Please explain in more detail.

Thank you for pointing out that this is not clear. McICA handles the interaction between clouds and radiation, and thus how the shortwave and longwave radiative flux profiles differ from those in a clear-sky situation. Then, the all-sky heating rates are computed based on the radiative flux divergence of the radiative flux profiles that the McICA computes. To clarify this, we suggest rephrasing line 124 as:

To compute the effects of clouds on the shortwave and longwave radiative flux profiles and corresponding atmospheric heating rates, the McICA...

Sections 3 and 4: The authors compare EarthCARE observations and RACMO simulations and clearly explain the analyzed features. However, their agreements or disagreements are, in my opinion, mainly explained subjectively. I believe the authors must provide statistical information, such as mean difference, root mean square difference, and correlation coefficient. If such quantitative model evaluation results are provided in this paper, I think this study could serve as a future benchmark for the development of polar regional climate models.

Our analysis is indeed mainly qualitative. As this study only focuses on two cases, statistical metrics might not represent the model performance accurately, and, therefore, we initially refrained from adding statistical information (apart from the histograms in Fig. 5 and Fig. 10). We plan to do a larger scale evaluation of 1-2 year of EarthCARE overpasses in the future, which would include a more statistical analysis, as this would be able to represent a larger period and the whole domain. However, for this study, after this has been pointed out by both reviewers, we see that some statistical information can strengthen our conclusions. We will therefore add some statistics and will mention explicitly that these numbers only apply to the cases analyzed in this study. We will make the following changes to the text:

Line 329:

... western part of the GrIS. For this case, most ice clouds are detected (probability of detection of 0.61), and only a few ice clouds are modeled in the wrong location (false alarm rate of 0.17). Although the ...

Line 344:

... not captured by RACMO. Because these liquid and mixed-phase layers are relatively small, modeling them in exactly the right location is difficult, which is indicated by a low probability of detection of 0.11 and a high false alarm rate of 0.96.

Line 351:

... with a mid-range IWC. On average, over the entire vertical profile, the simulated IWC is underestimated with a bias of $-5.8 \cdot 10^{-5}$ kg m^{-3} (relative underestimation of 67%) and shows relatively weak correlation (R^2 = 0.16) with the observed IWC.

Line 359:

... for this overpass. In line with the modeled IWC, the modeled snowfall rates over the vertical profile are on average underestimated (bias of $-4.7 \cdot 10^{-5}$ kg m^{-2} s^{-1}, equivalent to a relative underestimation of 65%) but show a higher correlation (R^2 = 0.39) with the observations. The snowfall ...

Line 404:

...of the detected mixed-phase layers, indicated by a low probability of detection of 0.06 and a high false alarm rate of 0.96 for liquid water.

Line 409:

...western part of the GrIS. This results in a slightly lower probability of detection of 0.59 and a higher false alarm rate of 0.25 for ice clouds than for the March case. Looking at the ...

Line 418:

...than the March case. Although over the vertical profile, the bias of $-5.3 \cdot 10^{-5}$ kg m^{-3} is slightly lower for this case, the relative underestimation is larger (77%), but the correlation is slightly higher (R^2 = 0.22).

Line 420:

... for this overpass. This is reflected in the larger negative bias of $-5.1 \cdot 10^{-5}$ kg m^{-2} s^{-1} (relative underestimation of 72%) over the whole profile and slightly lower correlation (R^2 = 0.37) than for the March case. Even though ...

Rephrasing and adding to lines 494-496:

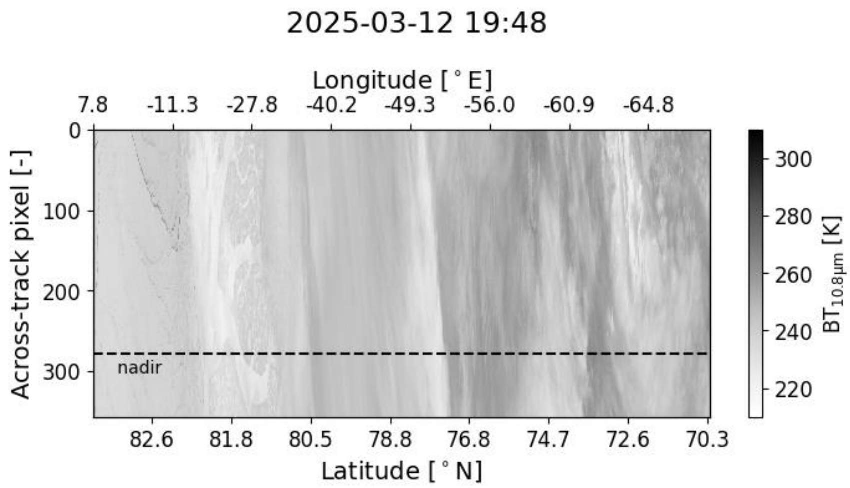
While these first case studies offer meaningful insights into cloud representation in RACMO, the small number of cases analyzed results in large uncertainty regarding the discrepancies between the EarthCARE observations and RACMO model results. The numbers presented in this study should thus be treated with caution, as they represent a small sample size. Therefore, a more comprehensive evaluation based on multiple months of EarthCARE observations will be necessary for a reliable evaluation and will guide model development.

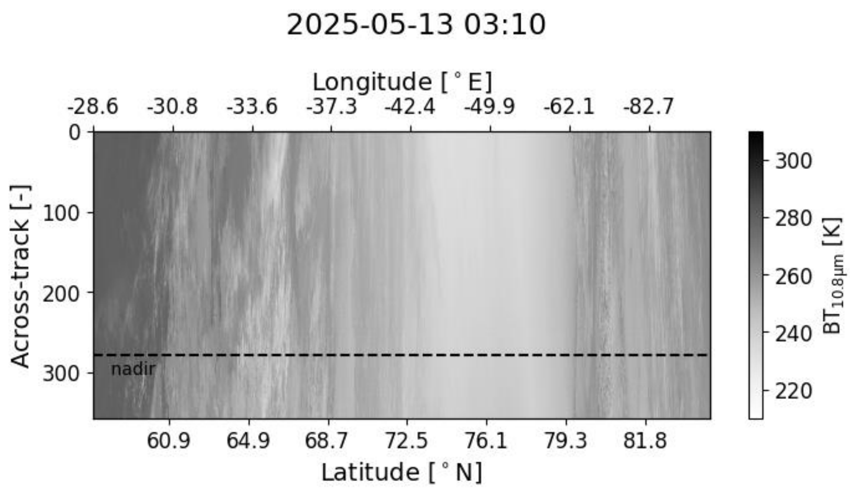
Sections 3 and 4: In general, it is difficult for a regional atmospheric model to simulate the exact timing and location of cloud formations. In other words, the cloud appearance times and locations simulated by a regional atmospheric model often disagree with reality. Therefore, I think it is necessary to use more model-derived data (e.g., data before and after the target time, and data from east and west of the satellite paths) to obtain more meaningful insights into the model's performance.

Although it is indeed difficult for an RCM to model clouds exactly at the correct timing and location, the use of a relatively small domain with nudging at the upper boundary does allow for obtaining relatively good correspondence to the observed cloud state. Additionally, we do aim to get as close as possible to the correct timing and location when working towards an improved model version. Specifically for polar RCMs, it can be very important to match the timing and location as closely as possible. Specifically in areas where snow- or ice-melt occurs, capturing the location and timing of clouds is crucial, as they can strongly influence melt by altering the radiative fluxes.

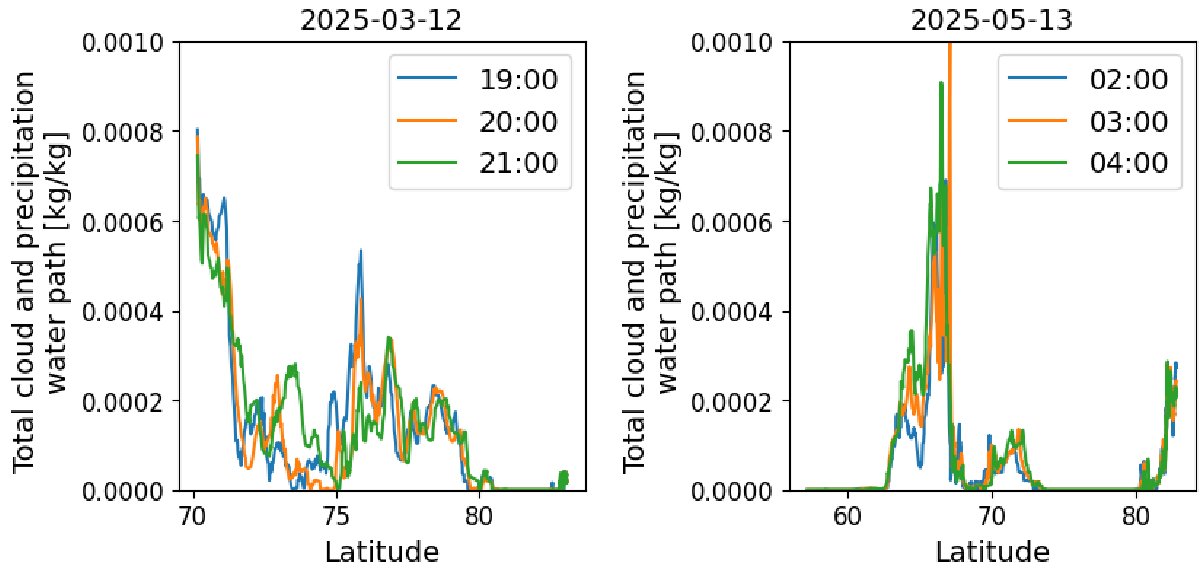
However, when selecting cases for this study, we aimed for cases where there was enough overlap in modeled and observed clouds. We indeed also found a few cases where the EarthCARE overpass was over or just next to a cloud edge, which could lead to large discrepancies with the RACMO output. Therefore, for this study, we have only considered cases where this was not the case and thus had lower across-track variability.

The low across-track variability for these cases can also be seen from the brightness temperature from the corresponding MSI observations (MSI-RGR-1C), which cover a wider (150 km) swath:





Regarding temporal variability, cloud systems are relatively slow in this region. For both cases, the along-track modeled total water paths for the three hours to the overpass time are shown below. In both cases, there is a strong temporal correlation: 0.93 (19:00–20:00) and 0.90 (20:00–21:00) for the first case, and 0.85 (02:00–03:00) and 0.90 (03:00–04:00) for the second case. Considering this high temporal correlation, differences in timing have likely not influenced the analysis strongly.



Considering this, we would like to refrain from including model data from neighboring times and locations. We will add a sentence on the importance of co-location in general to the method in line 185:

... not to influence the analysis. As clouds strongly influence melt, it is crucial to model them in the correct location and at the correct time to capture melt patterns as accurately as possible. Therefore, using co-located profiles will yield the fairest comparison.

We will also add that, for this study, this was a constraint for the selection of cases to line 263:

... to compare the two. To achieve this, cases with low across-track spatial variability were chosen, since this prevented situations in which an EarthCARE overpass would be close to a cloud edge, where a small shift in timing or spatial patterns could result in large differences in the vertical profiles. Since models struggle ...

L. 460 ~ 465 "These case studies suggest that some of our previous tuning choices should be reconsidered, such as the doubling of the snow sedimentation velocity, which now appears overestimated. Additionally, the process of conversion of ice to precipitating snow might also be overestimated, leading to overly rapid snow particle generation, resulting in ice clouds dissipating too quickly. Currently, the persistence of supercooled liquid layers might likely be suppressed by a too strong Wegener-Bergeron-Findeisen process, which converts too much liquid water into ice crystals.": My impression from this study is that it is too early to argue so. This is because the authors made only two short-period comparisons in a single year (2025) and a limited season (spring). I assume the RACMO team must achieve good model performance throughout a year to estimate a realistic surface mass balance of the ice sheet, meaning the authors must make such comparisons across multiple years and seasons to confirm whether the argument is truly valid.

The surface mass balance is indeed a very important constraint when tuning the model, which we also mention in lines 467-470. We also plan on using EarthCARE data for a longer period (see lines 494-496), as well as in-situ weather station and surface mass balance observations for our future model tuning. We do agree that we cannot conclude that all previous tuning should be changed based on these two cases, but it should be looked into, and we will therefore rephrase these lines as:

These first case studies suggest that some of our previous tuning choices should be re-evaluated, such as the doubling of the snow sedimentation velocity, which, for these cases, appears overestimated. Additionally, the process of converting ice to precipitating snow may also be overestimated, leading to overly rapid snow particle generation and resulting in ice clouds dissipating too quickly. Furthermore, the persistence of supercooled liquid layers might currently be suppressed by a too strong Wegener-Bergeron-Findeisen process. This would convert too much liquid water into ice crystals, which might explain in part the missing liquid layers in the RACMO simulation for these two cases.

Specific comments (minor)

Title: The polar regional climate model RACMO is well recognized in the global cryosphere community; however, I don't know whether it is also famous among the readers of the journal AMT. My impression is that it is better to add something like "the regional climate model" before RACMO2.4.

Thank you for pointing this out. We will rephrase the title accordingly:

Exploring new EarthCARE observations for evaluating Greenland clouds in the regional climate model RACMO2.4

L. 74 "a higher horizontal resolution": Can the authors add quantitative information for the horizontal resolution of the EarthCARE measurements?

For the CPR, this is mentioned in lines 151-152, for EarthCARE and CloudSAT. For ATLID, the horizontal resolution is mentioned in lines 141-142, but it is not compared to CALIPSO's horizontal resolution. The CALIPSO horizontal resolution is 333 m (Winker et al., 2007), which is poorer than both ATLID's 140 m sampling distance and 280 m effective resolution. We therefore propose to add the CALIPSO resolution to lines 141-142:

... an effective resolution of 280 m, compared to a horizontal resolution of 333 m for CALIPSO (Winker et al., 2007).

Combined products (like the classification used in this manuscript) are provided on a joint 1 km horizontal resolution grid (Mason et al., 2023). Therefore, we will change line 74 to:

...at a maximum horizontal resolution of 1 km (Mason et al., 2023), which is higher than ever before.

Sect. 2.2: Are the EarthCARE measurements evaluated against in-situ measurements, something like upper air observations with radiosondes? If yes, can the authors briefly introduce this point?

At the moment, the EarthCARE calibration and validation team is working on the evaluation of the EarthCARE observations and the improvement of the retrieval algorithms. Evaluation is, amongst others, done by comparing with lidar and radar observations from ground-based stations and from under-flight campaigns. However, as EarthCARE's launch was very recent, this is still ongoing work, of which very little has been published. We will include one study that has been published, which is a validation study of the CPR Doppler velocity.

Therefore, we will add a sentence in line 150:

... snowfall rate observations. A first comparison of the CPR's observed Doppler velocities with ground-based radar shows near-zero biases, indicating reliable observations of precipitation fall speeds (Kim et al., 2025). Compared to ...

L. 165: The names of five EarthCARE products are listed here. Can the authors briefly explain what properties we can obtain from these products?

We will add this as follows (note that we changed from ATL-NOM to ATL-EBD and from CPR-NOM to CPR-FMR as suggested by reviewer #2):

As we are primarily interested in cloud properties, this study focuses on the Level 2a ATL-EBD (lidar backscatter; Donovan et al., 2024), ATL-ICE (ice water content; Donovan et al., 2024), CPR-FMR (radar reflectivity; Kollias et al., 2023), and CPR-CLD (water content and precipitation rate; Mroz et al., 2023), and the Level 2b AC-TC (cloud, aerosol, and precipitation classification; Irbah et al., 2023) products.

L. 181 "the maximum modeled atmospheric wind speeds": At which level? Please explain.

This refers to the maximum over all model levels. When the time step of the model is too large, the model becomes numerically unstable, and the wind speed will blow up. When a certain wind speed threshold is crossed, the model will use a smaller time step. This is not very clear from line 181, so we propose to rephrase lines 180-182:

Depending on the numerical stability, which is determined from the maximum modeled atmospheric wind speed within the domain and the simulated month, RACMO uses a time step between one and five minutes for the Greenland domain on 5.5 km resolution.

L. 184 “Since cloud processes are relatively slow ~”: I understand that the authors want to state that the polar clouds are steady within ten minutes or so. Can the authors add a reference for this statement?

We will add the following reference:

Shupe, Matthew D. 2011. ‘Clouds at Arctic Atmospheric Observatories. Part II: Thermodynamic Phase Characteristics’. *Journal of Applied Meteorology and Climatology* 50(3). doi:10.1175/2010JAMC2468.1.

L. 274 ~ 275: To present the large-scale atmospheric flow towards the southeast clearly, I think it is better to expand the area in Fig. 2a. Please consider showing a figure with a larger domain during the target period by using the parent ERA5 data. This is also the case for Fig. 7.

Thank you for this suggestion. We agree that this would give a more complete picture of the large-scale flow, and would like to include it. However, we cannot directly expand the domain using the ERA5 data, as Fig. 2 shows the model output at 19:48 and Fig. 7 at 03:10, and ERA5 data at these specific time stamps is not available. We therefore decided to include ERA5 data from the closest hour (20:00 for Fig. 2 and 03:00 for Fig. 7). To distinguish between RACMO and ERA5, which do not have the same resolution and a slightly different time stamp, we highlighted the RACMO domain with a black box. The new figures are shown below:

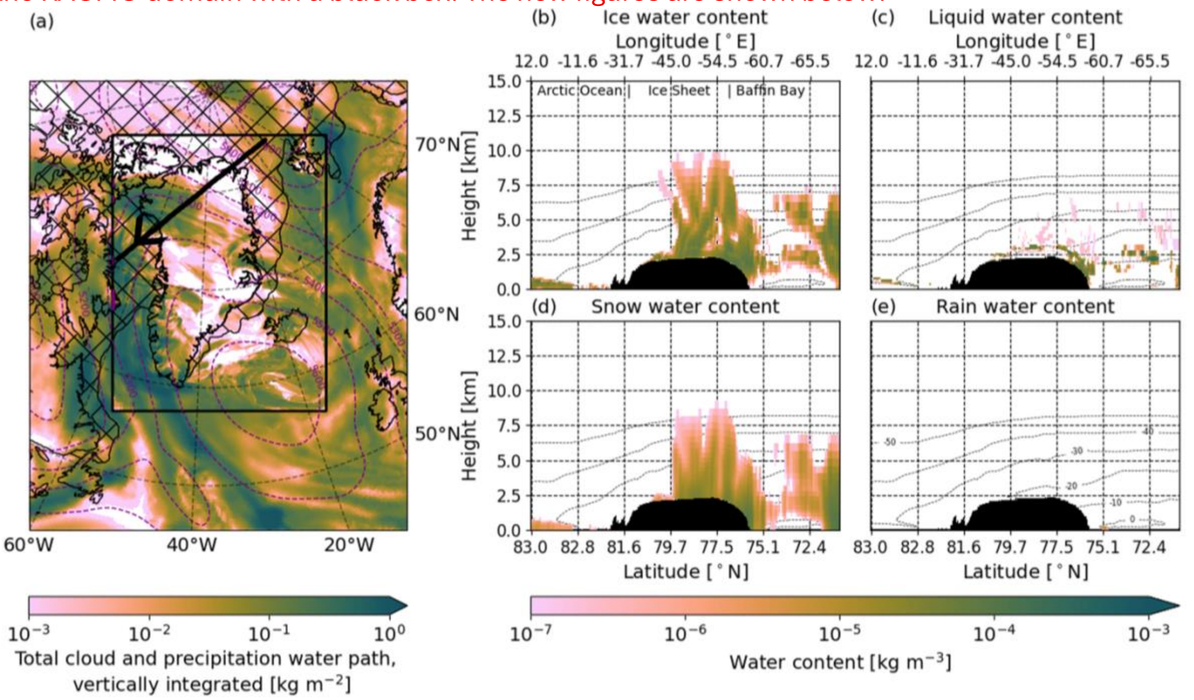


Figure 2. Modeled cloud scene on March 12th, 2025, 19:48 UTC. (a) Total cloud and precipitation water path, vertically integrated [kg m−2], as simulated by RACMO (within the black box) and ERA5 (at 20:00 UTC, outside the black box). The thick black line shows the EarthCARE overpass. The contours of the 500 hPa geopotential height [m] levels are shown in dashed purple lines. The hatched area indicates the presence of sea ice (sea ice extent larger than 15%). (b-e) Water content [kg m−3] as simulated by RACMO, for the co-located satellite overpass shown in (a), for (b) cloud ice, (c) cloud liquid water, (d) snow, and (e) rain. The dotted lines indicate the -50°C to 0°C temperature isotherms. Note that in (b-e) the x-axis follows the time coordinates. Hence, the latitude and longitude coordinates do not vary monotonically. In (b-e), black areas correspond to the topography.

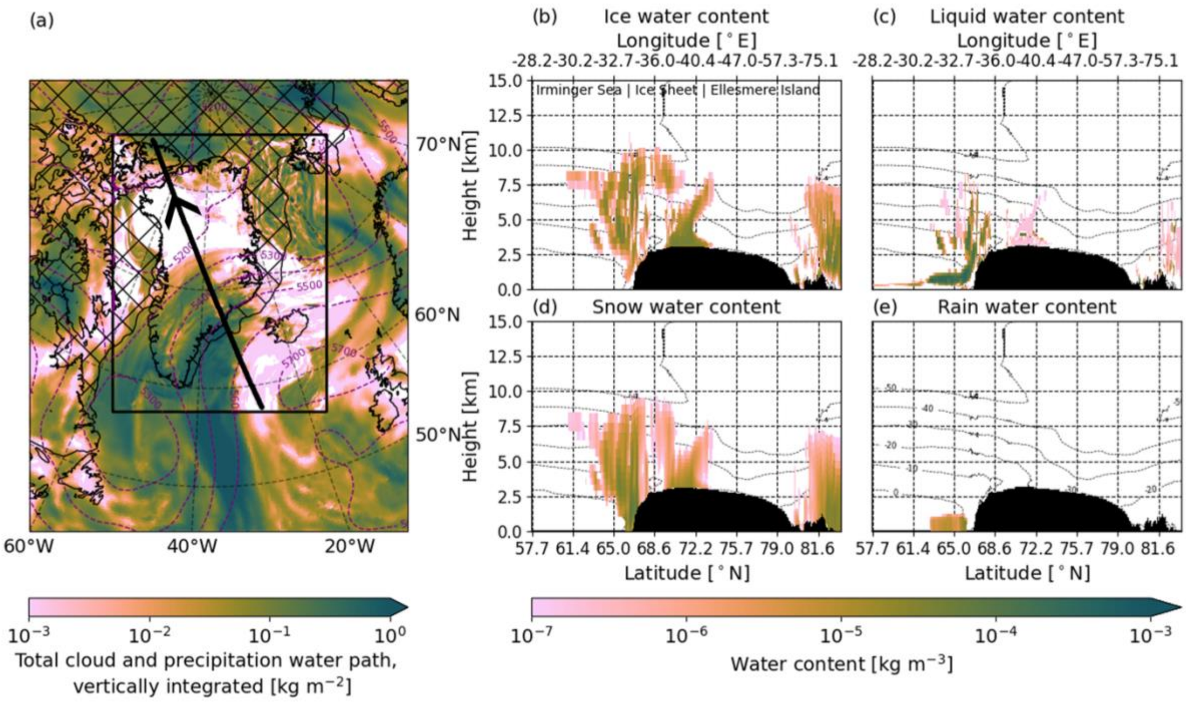


Figure 7. Modeled cloud scene on May 13th, 2025, 03:10 UTC. (a) Total cloud and precipitation water path, vertically integrated [kg m−2], as simulated by RACMO (within the black box) and ERA5 (at 03:00 UTC, outside the black box). The thick black line shows the EarthCARE overpass. The contours of the 500 hPa geopotential height [m] levels are shown in dashed purple lines. The hatched area indicates the presence of sea ice (sea ice extent larger than 15%). (b-e) Water content [kg m−3] as simulated by RACMO, for the co-located satellite overpass shown in (a), for (b) cloud ice, (c) cloud liquid water, (d) snow, and (e) rain. The dotted lines indicate the -50°C to 0°C temperature isotherms. Note that in (b-e) the x-axis follows the time coordinates. Hence, the latitude and longitude coordinates do not vary monotonically. In (b-e), black areas correspond to the topography.

L. 311 “The previous findings ~”: It is better to specify.

We will change this line to:

The differences in altitude and thickness of ice clouds are also indicated by the radar reflectivity (Fig. 3e-f).

Technical corrections

L. 48: I had an impression that the intention of the first sentence in this paragraph is similar to that of the previous paragraph (L. 30): Both sentences state that it is challenging for climate models to simulate polar clouds accurately. Suggest rephrasing “Evaluating cloud microphysical representation in climate models is particularly challenging for polar regions, as ground-based observations are limited (Shupe et al., 2013).” to something such as “Ground-based observations that can be used for the evaluation of cloud microphysical representation in climate models are limited (Shupe et al., 2013).”

Thanks for indicating this; these sentences are indeed very similar. We would like to change line 48 to something similar to your proposed sentence:

Ground-based observations in polar regions that can be used for the evaluation of cloud microphysical representation in climate models are limited (Shupe et al., 2013).

L. 72 ~ 74 & L. 76 ~ 78: I had an impression that the following two sentences explain almost the same thing. Can the authors merge them? “EarthCARE not only extends the CloudSat and CALIPSO observational record but also marks a big step forward by delivering the first exactly co-located measurements of clouds, aerosols, and radiation from space at a higher horizontal resolution than ever before.” and “By combining observations of the four different instruments, an atmospheric lidar, a cloud profiling radar, a multispectral imager, and a broadband radiometer, EarthCARE provides observations of the vertical structure of clouds, aerosols, and radiation in unprecedented detail."

The aim of lines 72-74 is to emphasize the exact co-location of the three observables (clouds, aerosols, and radiation), and this is explained further in lines 74-76. Lines 76-78 focus more on how they are measured (the four instruments). But this can be written more concisely:

EarthCARE not only extends the CloudSat and CALIPSO observational record but also marks a big step forward by delivering the first exactly co-located measurements of clouds, aerosols, and radiation from space. By combining observations of the four different instruments, a high spectral resolution atmospheric lidar, a Doppler cloud profiling radar, a multispectral imager, and a broadband radiometer, EarthCARE provides observations of the vertical structure of the atmosphere at a maximum horizontal resolution of 1 km (Mason et al., 2023), which is higher than ever before. Without a lag in observation time between the instruments, no assumptions regarding temporal evolution have to be made, yielding more accurate atmospheric profiles.

L. 95: "will" can be removed.

Thank you, we will remove it.

L. 127 "very": It sounds subjective. It is better to be removed.

We will remove it.

L. 140 "more accurate": Compared to what?

More accurate than when no particulate polarization is used, as it provides additional information on the particle shapes.

We will change lines 139-140 to make this clearer:

Use of a particulate polarization channel provides information on particle shapes, which increases the accuracy of the retrieved ice particle properties and aerosol types.

References:

Winker, David M., William H. Hunt, and Matthew J. McGill. 2007. ‘Initial performance assessment of CALIOP’. *Geophysical Research Letters* 34(19). doi:10.1029/2007GL030135.
Mason, Shannon L., Robin J. Hogan, Alessio Bozzo, and Nicola L. Pounder. 2023. ‘A Unified Synergistic Retrieval of Clouds, Aerosols, and Precipitation from EarthCARE: The ACM-CAP Product’. *Atmospheric Measurement Techniques* 16(13). doi:10.5194/amt-16-3459-2023.
Kim, Jiseob, Pavlos Kollias, Bernat Puigdomènech Treserras, Alessandro Battaglia, and Ivy Tan. 2025. ‘Evaluation of the EarthCARE Cloud Profiling Radar (CPR) Doppler Velocity Measurements Using Surface-Based Observations’. *Atmospheric Chemistry and Physics* 25(21). doi:10.5194/acp-25-15389-2025.
Shupe, Matthew D. 2011. ‘Clouds at Arctic Atmospheric Observatories. Part II: Thermodynamic Phase Characteristics’. *Journal of Applied Meteorology and Climatology* 50(3). doi:10.1175/2010JAMC2468.1.