Authors' Response to Reviews of

Cloud liquid water path detectability and retrieval accuracy from airborne passive microwave observations over Arctic sea ice

Nils Risse, Mario Mech, Catherine Prigent, Joshua J. Müller, and Susanne Crewell
Atmospheric Measurement Techniques,

RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

1. RC1, Prof. Dr. Christian Mätzler

1.1. General remark

RC: ***This manuscript describes an excellent experiment, possibly leading to an advancement in microwave remote sensing of the arctic ocean and atmosphere by a proper combination of forward models of microwave emission, SMRT and PAMTRA, for essential contributors, such as sea ice, snow, cloud liquid water, water vapour, and dry air. Due to the large number of physical parameters of the atmosphere and of the arctic ocean, the task required a delicate choice of observables, of variable and of fixed model parameters to get reasonable assessments. The observations consist of ERA5 data and of measurements from a large sensor package (HAMP) on a high-altitude aircraft (HALO) with microwave radiometers (and others) looking in nadir direction at frequencies between 22 and 190 GHz. The complexity of this work required several days of reading and thinking to get a reasonable understanding. Finally, the gain of insight was great. But I might have been lost without my experience with microwave signatures of sea ice, snow and tropospheric water because basic signatures are missing in this manuscript.***

AR: The authors would like to thank Prof. Dr. Christian Mätzler for providing highly valuable and constructive feedback on this manuscript. We have carefully considered all the comments and provided responses below.

We have added a figure to the manuscript showing the basic simulated TB signatures of model and state parameters at HAMP frequencies. See also our response to the corresponding major comment by the second reviewer.

1.2. Comments, questions and corrections

RC: ***1 Change: CWP to ILW. The essential parameter is called Cloud Water Path (CWP). Unfortunately, this name is not clear, and it is misleading in three ways: a) The word, path, is irritating, as it may indicate which path a cloud may take on its way in the atmosphere. But this is not the case. b) Cloud water also consists of water vapour in the air between the cloud droplets. The mass of of cloud droplets is usually smaller than the mass of the water vapour in the cloud. c) Clouds may also consist of frozen water. Since the authors understand CWP as the liquid water mass per horizontal surface area, the name should be called vertically Integrated Liquid Water (ILW) mass of clouds in the atmosphere. This corresponds well to the vertically Integrated Water Vapour (IWV) mass of the atmosphere. This quantity is correctly used in the manuscript.***

AR: We renamed "cloud water path" to "cloud liquid water path (CLWP)" in the text and figures. This avoids confusion with water vapor and ice, and aligns with the naming convention for Essential Climate Variables (ECV) by the Global Climate Observing System (GCOS).

RC: ***2 Line 4: "the variable sea ice and snow emission and scattering signatures partly mask the cloud signal..." In my view, the opposite is true: "the sea ice and snow emission and scattering signatures are partly masked by the atmosphere".***

AR: We changed this to: "Spaceborne microwave radiometers provide a high sensitivity to CLWP at pan-Arctic scales, but extracting this information over sea ice requires separation of surface and cloud emission."

RC: ***3 Line 53: What do you mean with "spatially resolved latent space representation of the sea ice"?***

AR: In general, the latent space means an abstract, compressed representation of complex data. We removed this terminology and replaced it with the exact meaning in the work by Geer (2024). They use a three-dimensional vector (latent space) to compress the sea ice emissivity at AMSR2 channels.

Geer, A. J. (2024). Simultaneous inference of sea ice state and surface emissivity model using machine learning and data assimilation. Journal of Advances in Modeling Earth Systems, 16, e2023MS004080. https://doi.org/10.1029/2023MS004080

RC: ***4 Figure 6d Simulated TB response: Shown are spectra of undefinded quantities "DeltaTB". Please correct to TB values or define DeltaTB.***

AR: We added a description of ΔT_b in the figure caption.

RC: ***5 Line 418: "Crossing of the warm air intrusion from north to south": Correct to "crossing from north to south of a warm air intrusion" (from south)***

AR: Done.

RC: ***6 Line 434: What do you mean with "artificial signals"***

AR: We changed this to "false detections".

RC: ***7 Line 439: To avoid misunderstandings, connect tails of linked adjectives in front of a substantive by hyphens, such as "very low wind-slab-correlation lengths". Also elswhere.***

AR: We rephrased the sentence: "The wind slab correlation length is very low within the precipitating system, likely due to the ambiguity with the CLWP signal."

RC: ***8 Line 440: Correct or clarify (Fig. C1)***

AR: Changed to "(Appendix C)".

RC: ***9 Appendix A: This is very limited information on atmospheric profiles. The limitation to ERA5 data is questionable, here. Warm and humid air inflows into the arctic area can change IWV by an order of magnitude within short time. Therefore, the example with 10% change of a rather dry troposphere is insufficient. Actual water vapour variations could be accounted for, e.g by pattern differences and/or short-time variations at and between 22 and 31 GHz. Also, what I found from ground-based observations is that under advective conditions, the temporal decrease of IWV often corresponds to the precipitation in between.***

AR: We agree that the spatiotemporal variability of IWV is not fully resolved by the $1\,\mathrm{h}$ temporal and $31\,\mathrm{km}$ spatial resolution of ERA5. Especially, warm air intrusions can exhibit a high variability in both space and time. However, under most conditions, the spatial gradients and temporal variability are moderate and well-represented by ERA5 as found from the comparison with dropsondes. In principle, the addition of IWV into the state vector would be possible within the optimal estimation framework. Exploiting spatiotemporal patterns might be possible, but there are currently no constraints in space included in the cost function. It should be noted that ideally, more high-frequency channels would be helpful when additionally retrieving IWV, which increases computational cost (Fig. Rev1 and Rev2). In this paper, we decided to focus on the window channels and the relatively stronger CLWP signal, and treat the IWV from ERA5 as true IWV as supported by the dropsonde comparison.

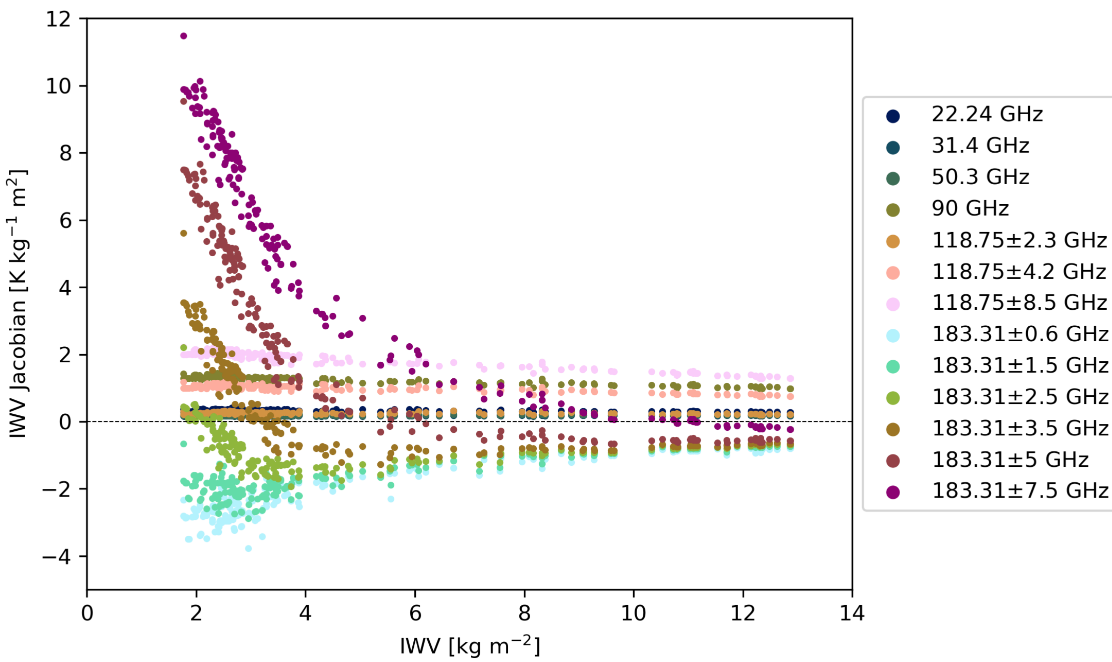

Figure Rev1: Simulated sensitivity of the T_b to changes in integrated water vapor (IWV). In total, 200 a priori profiles are randomly sampled along the *HALO* flight track to capture typical conditions during the campaign.

RC: ***10 Comment on the specularity parameter s: This parameter is most important at nadir view direction because of the largest difference between lambert scattering and specular reflection at a horizontal surface. On the other hand, there is no polarisation information in this case. Therefore, we need off-nadir observations, too, for real tests of the specularity***

AR: Yes, off-nadir observations at horizontal and vertical polarization would be ideal to provide information on specular contributions, i.e., angular and polarization dependence of the emissivity, at each channel. Here, we are limited to the nadir view. These have also been used to assess whether specular or Lambertian reflection is more appropriate under the assumption of smooth emissivity gradients at the wing of absorption lines (e.g., Guedj et al., 2010). Several studies have already shown that Lambertian reflection is more appropriate than specular reflection over snow-covered surfaces (Harlow, 2009; Guedj et al., 2010; Harlow, 2011; Harlow and Essery, 2012; Bormann, 2022). The assumption of pure Lambertian scattering is mainly chosen as the fraction of specular contribution is not known, and the computational cost would double when simulating specular and Lambertian contributions in PAMTRA. Also, the assumption of a fixed fractional specular contribution

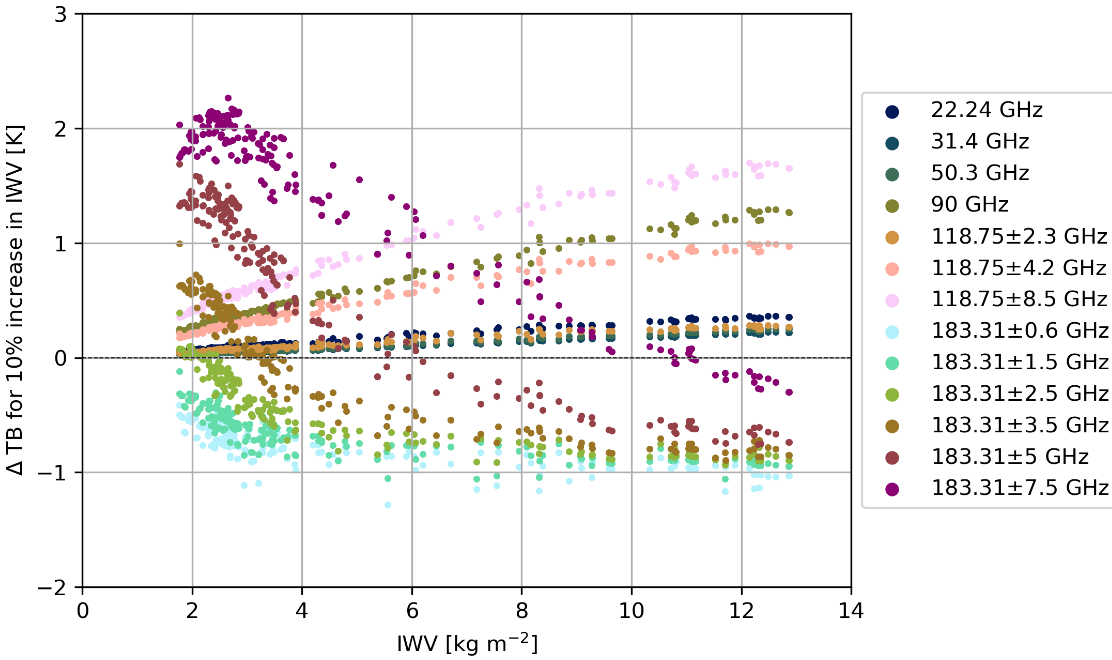

Figure Rev2: Same as Fig. Rev1, but expressed as a relative change in IWV of 10 %.

would be a simplification, as it likely depends on snow and ice properties that vary similarly to the emissivity on small spatial scales. This justifies the treatment of the specularity parameter as part of the forward model uncertainty. The mean T_b error due to the error of 0.25 in the specularity parameter depends on the channel as shown in Matzler (2005) and varies from -0.2 K at 22 GHz and -1.7 K at 50 GHz. Thus, potentially larger specular contributions at low frequencies (22 and 31 GHz) would have a minimal impact on the simulation.

Bormann, N.. (2022) Accounting for Lambertian reflection in the assimilation of microwave sounding radiances over snow and sea-ice. Quarterly Journal of the Royal Meteorological Society, 148(747), 2796–2813. Available from: https://doi.org/10.1002/qj.4337

R. C. Harlow, "Millimeter Microwave Emissivities and Effective Temperatures of Snow-Covered Surfaces: Evidence for Lambertian Surface Scattering," in IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 7, pp. 1957-1970, July 2009, doi: 10.1109/TGRS.2008.2011893.

R. C. Harlow, "Sea Ice Emissivities and Effective Temperatures at MHS Frequencies: An Analysis of Airborne Microwave Data Measured During Two Arctic Campaigns," in IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 4, pp. 1223-1237, April 2011, doi: 10.1109/TGRS.2010.2051555.

Matzler, C. (2005). On the determination of surface emissivity from satellite observations. IEEE Geoscience and remote sensing letters, 2(2), 160-163.