Authors' Response to Reviews of

Assessing the sea ice microwave emissivity up to submillimeter waves from airborne and satellite observations

Nils Risse, Mario Mech, Catherine Prigent, Gunnar Spreen, and Susanne Crewell

The Cryosphere, `https://doi.org/10.5194/egusphere-2024-179`

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

2. RC2, Dr. Melody Sandells

2.1. General comment

RC: ***This manuscript addresses the uncertainty in sea ice microwave emissivity representation for numerical weather prediction applications. Quantification of the sea ice contribution to satellite signals is crucial in order to separate surface and atmospheric contributions to satellite signals. This paper identifies sea ice type from microwave emissivity spectra via K-means clustering, demonstrates appropriateness of Lambertian scattering assumptions and investigates scaling issues by resampling airborne observations to satellite resolution and comparing with satellite data, considering resolution, incidence angle, polarisation as well as frequency. This manuscript is well-written and robust with justified assumptions and demonstrates that representative emissivity based on sea ice type is a reasonable approach and consequently that the spatial variability in sea ice properties must be accounted for. This manuscript is suitable for publication with minor amendments, and the following points considered in discussion:***

AR: The authors would like to thank Dr. Melody Sandells for their valuable time reviewing this manuscript and providing constructive feedback. We have carefully considered all comments and provided author responses below.

2.2. Line 39-41

RC: ***Please expand on the Hewison study to discuss what was found and how it relates to these results. This is already included around line 280, but what is needed here is to highlight the new frequencies in this approach, particularly given that the higher frequencies are more sensitive to surface type.***

AR: We extended the description of Hewison et al. (2002) by adding two sentences on their results, i.e., new ice, first-year ice, and multiyear ice emissivity spectra, with a focus on the higher frequencies.

> Hewison et al. (2002) calculated nadir emissivities ~~up~~ from 24 to 183 GHz of sea ice with different development stages from new to multiyear ice with similar instrumentation as in Hewison and English (1999). New ice emissivities were highest and slightly decreased from 0.95 at 89 GHz to 0.9 at 183 GHz. First-year ice emissivities decreased from 24 to 157 GHz and slightly increased from 157 to 183 GHz. This emissivity increase towards higher frequencies was also found for multiyear ice . Haggerty and Curry (2001) observed first-time emissivities up to 243 GHz at nadir at about 1 km^2 resolution.

2.3. Line 79-80

RC: ***Just to link with the previous section state that the Polar 5 carried the MiRAC and KT-19 instruments (see comment for line 156).***

AR: We added another sentence to mention the remote sensing instrumentation on board Polar 5.

> The research flights (RFs) with the Polar 5 aircraft (Wesche et al., 2016) from the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) covered the Fram Strait northwest of Svalbard, Norway (Fig. 1). *Polar 5* carried the microwave package MiRAC, the thermal infrared sensor KT-19, and a visual camera, among other instruments.

2.4. Line 81

RC: ***'1). Various sea ice characteristics were observed… ': specify this is from the airborne observations as no in situ measurements were made.***

AR: We modified the sentence to avoid confusion with in situ measurements.

> Various sea ice characteristics were observed with *Polar 5* during ACLOUD, i.e., RF23 on 25 June and RF25 on 26 June 2017, and AFLUX, i.e., RF08 on 31 March, RF14 on 8 April, and RF15 on 11 April 2019, under clear-sky conditions over sea ice suitable for emissivity estimation.

2.5. Line 84

RC: ***Is ACLOUD firstyear, multiyear or a mix or ice types? The description for AFLUX was very helpful – please include a comparable description for ACLOUD.***

AR: The sea ice type retrievals, which are based on microwave observations, provide no information during the melt season, because the backscatter and emission signals of first- and multiyear ice become more similar (e.g., Lindell and Long, 2016). For the Arctic, the multiyear ice concentration products are typically available from May to October. The AMSR2/ASCAT product used here provides a classification until 8 May 2017, which is 48 days before the first ACLOUD flight where we derived emissivities. Therefore, no sea ice type was mentioned for the two ACLOUD flights. Instead, we mention the presence of melt ponds and open water in between individual ice floes. We clarify this by adding "wintertime" to the multiyear ice product description in Sect. 2.4 (line 169).

Lindell DB, Long DG. Multiyear Arctic Ice Classification Using ASCAT and SSMIS. Remote Sensing. 2016; 8(4):294. https://doi.org/10.3390/rs8040294

> Finally, three data products add surface information, i.e., daily sea ice concentration maps of the University of Bremen with $6.25\times6.25\ \mathrm{km}^2$ resolution based on AMSR2 (Spreen et al., 2008), daily wintertime multiyear ice concentration maps of the University of Bremen with $12.5\times12.5\ \mathrm{km}^2$ resolution based on AMSR2 and the Advanced Scatterometer (ASCAT; Melsheimer and Spreen, 2022), and Sentinel-2B Level 2A visual images with $20\times20\ \mathrm{m}^2$ resolution (European Space Agency, 2021).

2.6. Line 88

RC: ***How was the integrated water vapour measured? Add a link to (presumably) section 2.4.***

AR: The integrated water vapor was derived from the in situ atmospheric profiles from dropsondes, radiosondes, and the aircraft's nose boom as described in Sect. 2.4. These profiles are also used for the emissivity calculation. We added a link to Sect. 2.4 in the revised manuscript.

> The integrated water vapor, derived from in situ observations (see Sect. 2.4), is about 10 to 10.3 $\mathrm{kg\,m^{-2}}$ during the two ACLOUD flights and 1.3 to 2 $\mathrm{kg\,m^{-2}}$ during the three AFLUX flights, which indicates reduced water vapor emissions and high atmospheric transmissivity during AFLUX.

2.7. Figure 1

RC: ***Please use a different colour scale to distinguish between RF23 and RF25 and between RF14 and RF15. Perhaps use different line thicknesses or line type.***

AR: We changed the line colors and widths to improve the visual clarity.

2.8. Table 1

RC: ***Add 'Passive' into the table caption and consider including the KT19 sensor characteristics.***

AR: We added passive into the table caption.

> Specifications of the passive MiRAC-A channel and MiRAC-P ~~channels~~.

AR: We excluded KT-19 from the table to solely list passive microwave channels. However, we agree that it is useful to compare the incidence angle and field of view information of these sensors. The information on the incidence angle is currently not mentioned and we added it in Sect. 2.4, line 156 (see the response to the comment on line 156).

2.9. Line 145

RC: ***It would be useful to remind the reader here that MiRAC 89GHz is only available at 25 deg.***

AR: We clarified this in the text.

> However, MiRAC's 89 GHz channel ~~with~~ , which measures under horizontal polarization at 25°, is not directly comparable with the satellite channels because MHS and ATMS measure mostly vertically polarized TB near this incidence angle, and SSMIS and AMSR2 measure at higher incidence angles.

2.10. Line 156

RC: ***This is the first mention of the KT-19 sensor (apart from line 119) – presumably also on the Polar 5, but please clarify.***

AR: Yes, the KT-19 is also on board Polar 5 and we added it to the sentence. This revised sentence also includes parts of the comment on Table 1 to avoid duplicate versions.

> The ~~airborne~~ KT-19 on board *Polar 5* provides infrared TBs integrated over the atmospheric window from 9.6 to 11.5 µm with 1 s resolution under an opening angle of 2° at nadir.

2.11. Line 178

RC: ***What is the estimated drift rate and how was this determined?***

AR: Climatological studies such as Kaur et al. (2018) found sea ice drift rates of about 8 to 10 $\mathrm{km/d}$ for the Fram Strait region. We also looked at daily sea ice drift data from the National Snow and Ice Data Center(NSIDC; Tschudi et al., 2020). We added this to the revised manuscript with an analysis of the temporal variability based on the RC1 comment on line 177.

Kaur S, Lukovich JV, Ehn JK, Barber DG. Higher-order statistical moments to analyse Arctic sea-ice drift patterns. Annals of Glaciology. 2020;61(83):464-471. doi:10.1017/aog.2021.6

Tschudi, M. A., Meier, W. N., and Stewart, J. S.: An enhancement to sea ice motion and age products at the National Snow and Ice Data Center (NSIDC), The Cryosphere, 14, 1519–1536, https://doi.org/10.5194/tc-14-1519-2020, 2020.

> We ensure simultaneous observations by filtering collocations within a ±2 h window, which maximizes the number of satellite overpasses and minimizes the effects of sea ice drift. The sea ice drift during the flights is less than 1 kmh^{-1} based on data from the National Snow and Ice Data Center (NSIDC; Tschudi et al., 2020), and spatial variability exceeds temporal variability (not shown).

2.12. Line 184

RC: ***Consider moving 'during ACLOUD (AFLUX)' to after 'overflights' so the meaning is better conveyed before the brackets are used. Could the information in this section be better displayed as a table?***

AR: We rearranged the sentence. Yes, the information on the number of satellite overflights and collocated footprints is more useful inside a table. Also, the number of satellite footprints without channel failure, e.g., 150 GHz of DMSP-F18/SSMIS (mentioned in Sect. 2.3), is important. We already provided this information in the results section combined with the emissivity statistics (see Tab. 4 and 5 for MHS and ATMS during AFLUX and Fig. 8 for all channels).

AR: Also, we noticed a mistake in the code where the distance threshold to the shoreline was 7.5 km instead of 8 km for MHS, ATMS, and SSMIS. This lead to the exclusion of one SSMIS footprint. We modified the number in the following sentence in the revised manuscript. The Fig. 8 of the manuscript will also be updated, but the change is hardly visible.

> The number of satellite overflights during ACLOUD (AFLUX) with collocated footprints from MHS, ATMS, SSMIS, and AMSR2 is 15 (23), 0 (8), 11 (26), and 2 (9) ~~during ACLOUD (AFLUX)~~, respectively. We matched channels near 89 GHz with MiRAC-A and above 100 GHz with MiRAC-P. The number of satellite footprints collocated with MiRAC at 89 GHz during ACLOUD (AFLUX) is 87 (86), 0 (34), ~~108~~ 107 (175), and 23 (159) for MHS, ATMS, SSMIS, and AMSR2, respectively.

2.13. Line 255

RC: ***Are the numbers in brackets for ACLOUD or AFLUX? In general it's better to write this out in full for ease of reading.***

AR: This sentence describes the difference between specular and Lambertian emissivities as a function of Lambertian emissivity. We modified this sentence along with line 401 based on the comment of RC1 on line 401 and provided both revisions under that comment.

2.14. Line 262

RC: ***'We observe predominantly snow-covered sea ice over the transect's initial 7 km' – is this from right to left as per Westerly flight, or left to right as per numbering in Fig 3?***

AR: This sentence refers to the part from 0 to 7 km, as drawn in Fig. 3. To avoid confusion with the flight direction, we clarified the sentence.

> We observe predominantly snow-covered sea ice ~~over the transect's initial~~ from 0 to 7 km.

2.15. Line 263

RC: ***Typo: 'Word' -> 'World'***

AR: Done.

2.16. Line 290

RC: ***'The ±8 K surface temperature uncertainty causes the highest emissivity uncertainty for all channels.' Where is this demonstrated?***

AR: This is provided as additional information and is not shown in Fig. 3, which indicates only the total error. We modified the sentence now by adding "not shown". Generally, this result originates from the error calculation that we describe in Sect. 3.2.

> The ± 8 K surface temperature uncertainty causes the highest emissivity uncertainty for all channels (not shown) .

2.17. Line 304

RC: ***'and we found no significant changes in the shapes of the histograms (not shown)'. What statistical test was used?***

AR: This statement is based on a comparison of the emissivity distributions with and without matching the footprints of MiRAC-A and -P. We performed a Kolmogorov–Smirnov test, which indicated that the samples do not originate from the same distribution. However, one must consider that emissivity biases vary regionally, i.e., temperature gradients in the snow and sea ice, air temperature biases, and relative humidity biases. This causes differences in the emissivity distributions for our limited number of flights. We modified the sentence of the revised manuscript and removed the word "significant."

> The 89 GHz and 183 to 340 GHz histograms include different samples due to the exclusion of low flight altitudes at 89 GHz, which introduces a potential inconsistency (Table 3). Therefore, we compared these histograms with those from instantaneous measurements where all channels sample the same sea ice, and we found no ~~significant~~ changes in the shapes of the histograms that exceed the estimated emissivity uncertainties (not shown).

2.18. Figure 3

RC: ***Please put this through a colour blind checker, particularly fig 3j, where it's hard to distinguish between 183 +/- 2.5 and 3.5 GHz bands.***

AR: We fixed this in the revised version.

2.19. Figure 4

RC: ***Please use a different colour scheme to distinguish between the two ACLOUD flights.***

AR: We updated the plot with the new colors, as in Fig. 1.

2.20. Line 351

RC: ***What test of significance was performed?***

AR: The word significant implies statistical tests and has been used in the wrong context here. We modified the sentence while retaining its meaning.

> However, the emissivity variability at both frequencies is still ~~significant~~ notable and depends on the sea ice type, with the highest contrast between multiyear ice and nilas.

2.21. Line 368

RC: ***'Hence, the satellite footprint contains mean conditions where significant small-scale variability averages out.' I am unsure what is meant by this and how it relates to the previous sentences – please could you clarify?***

AR: The sentence aimed at summarizing the findings from Fig. 6b of the manuscript, which shows that a high emissivity variability occurs on hectometer scales. This high emissivity variability reduces with increasing footprint sizes up to the satellite scale. We agree that the sentence is unclear and adjusted it to the following:

> Hence, the larger satellite footprint ~~contains mean conditions where significant small-scale variability~~ averages out small-scale emissivity variations.

2.22. Line 382

RC: ***'The limited spatial coverage of MiRAC causes slightly higher emissivity variability compared to MHS and ATMS, as MiRAC only captures a narrow strip of the satellite footprint'. Why this rather than simply the higher resolution of MiRAC?***

AR: The sentence was not precise and we modified it to convey the message that some areas are not well represented due to the incomplete coverage of the satellite footprint by MiRAC. The higher resolution of MiRAC will not be effective anymore after averaging it onto the satellite footprint.

> The limited spatial coverage of MiRAC causes ~~slightly higher emissivity variability compared to~~ deviations from MHS and ATMS, as MiRAC only captures a narrow strip of the satellite footprint, e.g., during AFLUX RF08 near 80.4° N, 5° E (Fig. 7a) leading to the highest emissivity bias (Fig. 7d).

2.23. Figure 6

RC: ***Does the cluster colour scheme relate to the emissivity colour palette?***

AR: The cluster colors are extracted from the same color map that is used for the emissivities. The cluster numbers were sorted such that the emissivity increases from cluster 1 to 4 at 89 GHz (see Fig. 5). Therefore, the dark color of cluster 1 corresponds to lower emissivities and the bright color of cluster 4 corresponds to higher emissivities.

2.24. Line 396

RC: ***As the satellites have different footprints 'equivalent spatial sampling' may be better than 'equal spatial sampling'***

AR: We modified the respective sentence.

> The MiRAC observations are averaged to the footprints of each satellite instrument to ensure ~~equal~~ equivalent spatial sampling.

2.25. Figure 7(m)

RC: ***What is in the wider satellite footprint that is causing the higher emissivity in the western tip?***

AR: We identified a mistake in Fig. 7. The third column does not show channel 2 from MHS (157 GHz) and channel 17 from ATMS (165.5 GHz) as also indicated in the label, but channel 5 from MHS (190.31 GHz) and channel 18 from ATMS (183.31±7.5 GHz). The feature is less pronounced in the 157 and 165.5 GHz channels of MHS and ATMS and likely relates to water vapor or temperature gradients that are not represented by our in situ profile. Another reason for the emissivity difference between MiRAC and MHS/ATMS are lower NE23 surface temperatures compared to KT-19

2.26. Line 416

RC: ***'Additionally, AMSR2 shows higher variability due to its smaller footprint than SSMIS'. This conflicts with ACLOUD IQR being smaller at Vpol for AMSR2 than SSMIS in Fig 8a.***

AR: We explain this discrepancy by the few collocated footprints of AMSR2 with MiRAC during ACLOUD RF23 (see the low count in Fig. 8a). For AFLUX, the number of footprints for SSMIS and AMSR2 is similar. We modified the sentence to indicate this better.

> ~~Additionally,~~ For AFLUX, where the footprint count of SSMIS and AMSR2 is comparable, AMSR2 shows higher variability due to its smaller footprint than SSMIS.

2.27. Line 469

RC: ***'Surface temperature assumption: Using the surface skin temperature instead of the emitting layer temperature imposes a frequency-dependent bias on the emissivity during AFLUX'. How much does this assumption influence the conclusion that the emissivity spectra are relatively flat?***

AR: We expect differences in the emitting layer temperature, especially between 89 and 150 GHz based on calculated penetration depths in Tonboe et al. (2006) and simulated emitting layer temperatures in Tonboe (2010). As penetration depth decreases toward higher frequencies, the emitting layer temperature lies closer to the skin temperature. Therefore, the frequency-dependent temperature bias would decrease towards 340 GHz. However, the effect of surface temperature on the emissivity is frequency-dependent as well for the method we use, with higher effects at higher frequencies. We expect that the bias lies within the uncertainties we provide in Tab. 3. Therefore, it would not largely affect the assumption that the emissivity spectra are relatively flat.