Answers to comments of Review #1

We gratefully thank the reviewers for the positive feedback on our submitted manuscript. We appreciate the time they took to extensively read and comment on the given manuscript. The constructive comments are very helpful for the improvement of the manuscript. Our replies to the referees' comments are structured as follows:

Referee's comments in italic – line numbers according to initially submitted manuscript

Authors' responses in roman – line numbers according to adjusted manuscript. **Citations from the initial and the adjusted manuscript are given in bold.**

The discussion of the important terms is inconsistent and sometimes confusing in the text. I recommend distinguishing explicitly between LW (TIR) and SW terms throughout. This would start by expanding eqs (1) and (2) to define separate terms for LW and SW using subscripts and then referring to those terms as well as their summations, CRE_{SW}, CRE_{LW}, CRE_{total} explicitly throughout the text.

We agree that, sometimes, the terms were used in a slightly confusing way. E. g., we sometimes only referred to the solar or TIR CRE as CRE without specifying it further. To overcome this issue, we introduced the terms CRE_{sol}, CRE_{TIR} and CRE_{tot} to refer to the solar, TIR and the total CRE. Therefore, we also split our equations into two as suggested. We changed the text around equations 1 and 2 as follows:

"**The surface REB is investigated separately for the solar and TIR spectral ranges and quantified by the solar and TIR net irradiances, $F_{\mathrm{net,sol}}$ and $F_{\mathrm{net,TIR}}$, respectively. The net irradiances are defined as the difference of the respective downward ($F_{\mathrm{sol}}^{\downarrow}$ and $F_{\mathrm{TIR}}^{\downarrow}$) and upward ($F_{\mathrm{sol}}^{\uparrow}$ and $F_{\mathrm{TIR}}^{\uparrow}$) irradiances:**

(new equation 1): $F_{\mathrm{net,sol}} = F_{\mathrm{sol}}^{\downarrow} - F_{\mathrm{sol}}^{\uparrow}$

(new equation 2): $F_{\mathrm{net,TIR}} = F_{\mathrm{TIR}}^{\downarrow} - F_{\mathrm{TIR}}^{\uparrow}$

The cloud impact on the REB is quantified by the solar and TIR cloud radiative effect (CRE), CRE_{sol} and CRE_{TIR}, respectively, which is also referred to as cloud radiative forcing (Ramanathan et al., 1989). It is derived from the net irradiances in cloudy ($F_{\mathrm{net,sol,cld}}$ and $F_{\mathrm{net,TIR,cld}}$) and cloud-free ($F_{\mathrm{net,sol,cf}}$ and $F_{\mathrm{net,TIR,cf}}$) atmospheric conditions:

(new equation 3): $CRE_{\mathrm{sol}} = F_{\mathrm{net,sol,cld}} - F_{\mathrm{net,sol,cf}}$

(new equation 4): $CRE_{\mathrm{TIR}} = F_{\mathrm{net,TIR,cld}} - F_{\mathrm{net,TIR,cf}}$

The sum of CRE_{sol} and CRE_{TIR} gives the total CRE CRE_{tot}. It depends on both …"

Additionally, we now introduce the terms CRE_{sol}, CRE_{TIR} and CRE_{tot} already in the abstract and replaced "solar CRE", "TIR CRE" and "total CRE" as well as the unclear occurrences of "CRE", but also, e. g., "upward irradiance" or "downward irradiance" by the respective symbols throughout the text. However, when comparing two CRE values, we mostly stuck to the terms "solar cooling effect" or "TIR warming effect" since the wording "decreasing CRE_{sol}" instead of "stronger solar cooling effect" sounds counterintuitive.

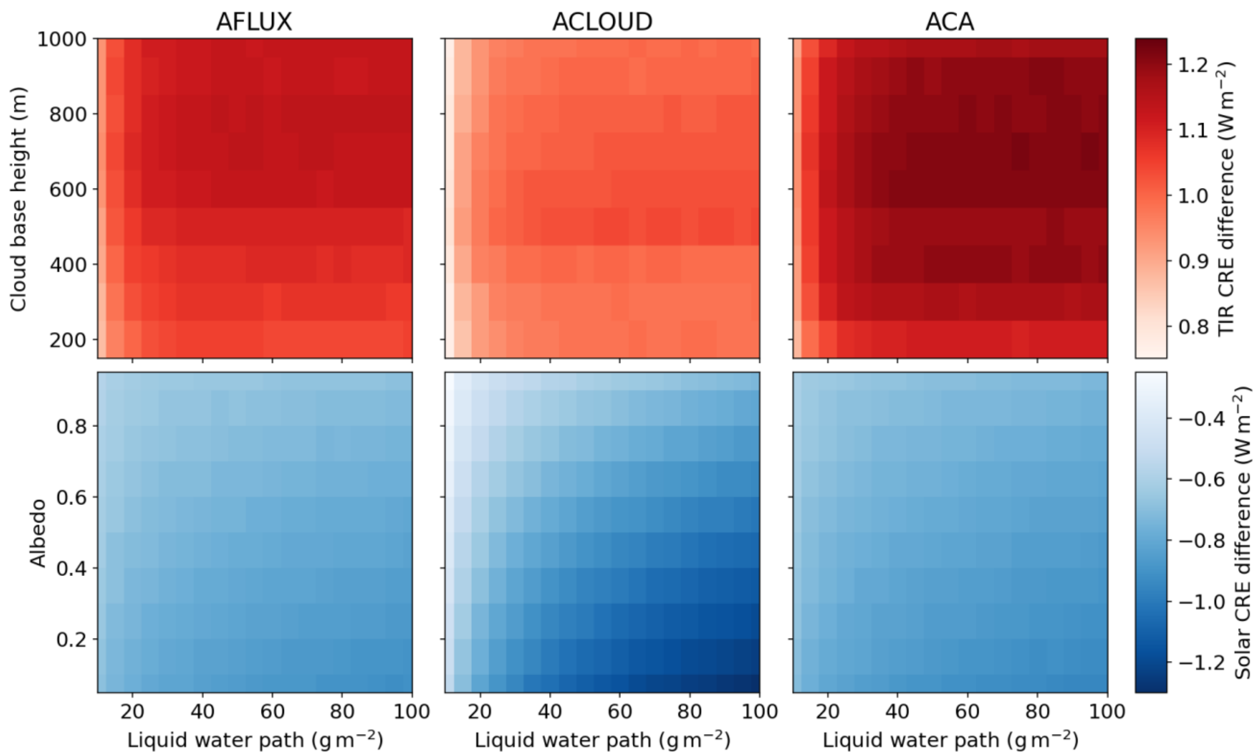

Figure 1: Difference of CRE_{TIR} (upper panels) and CRE_{sol} (lower panels) between a flight altitude of 100 m and the surface for the different campaigns, depending on cloud base height, albedo, and LWP. (Figure not included in the manuscript)

The CRE presented are advertised as referenceable to the surface but I don't see any description of the atmospheric corrections necessary to transfer the SW and LW observations from the altitude of the aircraft to the surface. If you think that the aircraft was low enough that no correction is needed, some evidence that the flux divergence between the aircraft and the surface is negligible is warranted.

You are right that the CRE we observe at flight altitude differs from the real surface CRE due to the remaining atmospheric influence between the aircraft and the surface. To quantify this effect, we performed additional radiative transfer simulations for both CRE_{sol} and CRE_{TIR} at the surface and in 100 m altitude (the majority of the low-level measurements were performed below this altitude). In general, the simulation setup was identical to the description in the manuscript. Notwithstanding, for each campaign, the mean thermodynamic profile obtained during aircraft ascents and descents was used as input for both spectral ranges. For CRE_{sol}, the surface albedo was varied between 0 and 1 and a 200 m thick cloud based at 400 m was included with different LWP. The SZA was set to the mean campaign values. In the TIR range, 250 m thick clouds with different base heights and LWPs were added. The differences between the CRE at the surface and in 100 m are shown in Fig. 1. It turns out that CRE_{sol} in this altitude is slightly underestimated compared to the surface level, while CRE_{TIR} is slightly overestimated. For the situations present in our observations, the underestimation of CRE_{sol} never exceeded 1.3 W m^{-2}. The overestimation of CRE_{TIR} does not exceed 1.25 W m^{-2}. Consequently, we conclude that the CRE derived in low flight altitudes is a good estimate of the surface CRE. Cloud, surface and atmospheric properties will impact the CRE similarly in both altitudes.

Sometimes sea smoke was present in the lowest 100 m below the aircraft. In this case, a significantly different CRE could be expected at the surface. However, the focus in this study is on the radiative impact of clouds above the flight altitude. A correction of the sea smoke effects and transferring the CRE derived in flight altitude to the surface CRE would mislead the interpretation of the CRE of the elevated clouds. Therefore, we stick to analyzing the CRE in flight altitude.

We added the following sentences to the text: "**Although the measurements were not performed directly at the surface, the impact of the atmosphere below the aircraft is small if no cloud or fog layers are present there. For a flight altitude of 100 m, radiative transfer simulations for different cloud and albedo properties revealed an underestimation of less than 1.3 W m^{-2} for CRE_{sol} and an overestimation of less than 1.25 W m^{-2} for CRE_{TIR} compared to the surface. Larger differences are expected for the occasionally occurring sea smoke below the aircraft. However, the analysis focuses on the radiative effect of clouds above the flight altitude, i. e., neglecting the sea smoke. Only in case of indirect effects (e. g., change of the measured albedo by the sea smoke), its influence is discussed in the remainder of this study.**"

Line 310: I agree that locally and briefly downwelling shortwave at the surface can exceed TOA irradiance and could cause real positive values of solar CRE. However, I'm skeptical (in particular given the altitude of the aircraft) that this is such a significant effect on the surface values so as to make up as large a fraction of the samples as you show in Figure 7. Indeed, mode 1 ("cloud free"!) appears to be associated with positive solar CRE almost all the time. Something is amiss. Maybe you could validate your simulated clear-sky SW with observed SW under clear skies to be sure that (a) there is not a bias and (b) to potentially explain the preponderance of positive values as uncertainty in the clear term. If there are not enough statistics from the campaigns, perhaps a longer record of validation from Ny-Alesund can be performed.

Just to avoid confusion and to clarify: We don't claim that, for the situations with positive CRE_{sol}, the measured $F^{\downarrow}_{\mathrm{sol}}$ exceeds $F^{\downarrow}_{\mathrm{sol}}$ at TOA. Rather, we compare to simulated conditions (including an atmosphere), where simply no cloud is present. Anyway, as we agreed, broken clouds can briefly exceed the downward irradiance, which, however, does not depend on altitude.

Positive CRE_{sol} by broken and thin clouds is reported to be a common feature (e. g., Mol et al., 2023, https://doi.org/10.1029/2022JD037894). For our observations, it has to be noted that only two flights (31 March and 8 April, Fig. 2) contributed to the positive values of the CRE_{sol} distribution over open ocean (albedo values below 0.2, mode 1). To illustrate the occurrence of positive CRE_{sol} in more detail, time series of the measured and the cloud-free simulated $F^{\downarrow}_{\mathrm{sol}}$, the measured and retrieved cloud-free albedo and the obtained CRE_{sol} are shown in Fig. 3 for 8 April. For the first 30 minutes, the measured and simulated $F^{\downarrow}_{\mathrm{sol}}$ agreed well, which resulted in a CRE_{sol} of 0 W m^{-2} and indicates that there is no major discrepancy between simulation and observation in cloud-free conditions. Roughly between 11:15 and 11:35, the measured $F^{\downarrow}_{\mathrm{sol}}$ was highly variable and partly exceeded the cloud-free simulated $F^{\downarrow}_{\mathrm{sol}}$, which led to the frequently observed positive CRE_{sol} values. The median solar CRE was 16 W m^{-2}. During

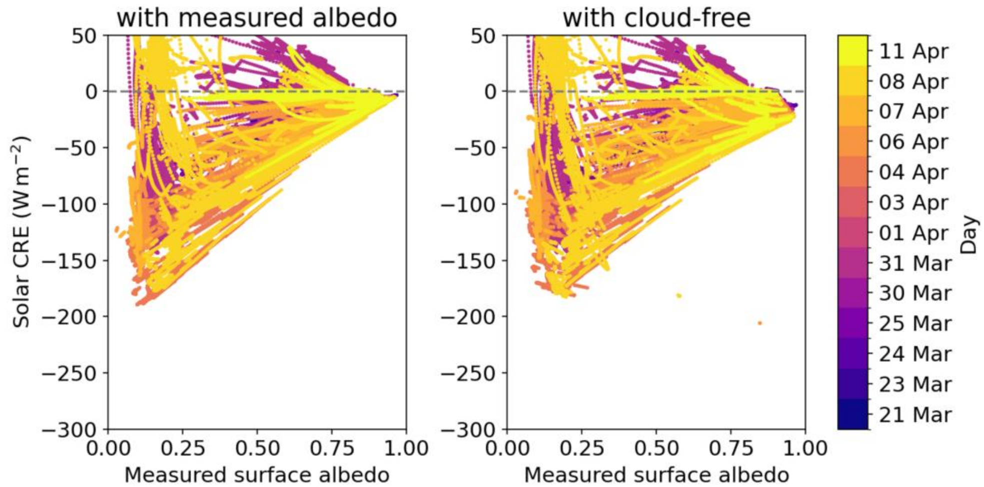

Figure 2: Scatter plot of the CRE_{sol} as function of the measured surface albedo. The colors represent the flights (days) during which the respective measurements were obtained. (Figure not included in the manuscript)

this time period, the cloud field above the aircraft transitioned from overcast to cloud-free conditions and mostly consisted of cumulus clouds (Fig. 4). According to Mol et al. (2023), such transition periods with broken cumulus clouds are predestinated to cause $F_{\mathrm{sol}}^{\downarrow}$ values exceeding the cloud-free $F_{\mathrm{sol}}^{\downarrow}$ (see their Figs. 1 and 4).

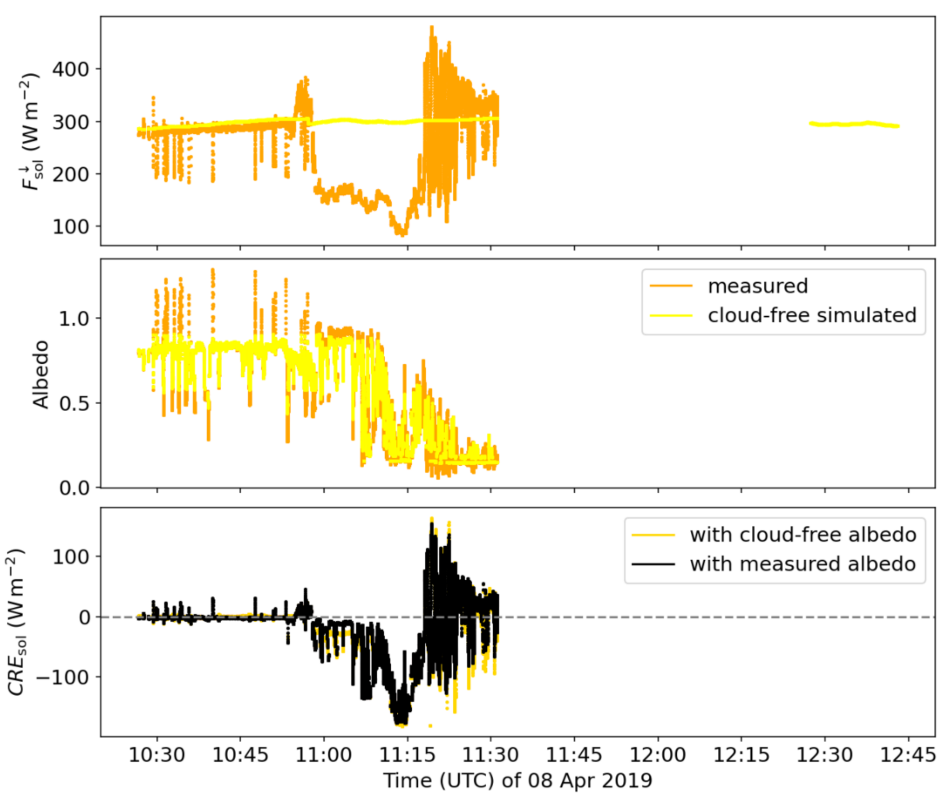

Figure 3: Time series of the measured and the cloud-free simulated $F_{sol}^{\downarrow}$ (upper panel), the measured and retrieved cloud-free albedo (middle panel) and the obtained CRE_{sol} using the measured or cloud-free albedo (lower panel). (Figure not included in the manuscript)

Broken cloud situations like this were not infrequently sampled during AFLUX over open ocean. Thus, these observations shape a mode peaking at positive CRE_{sol} values.

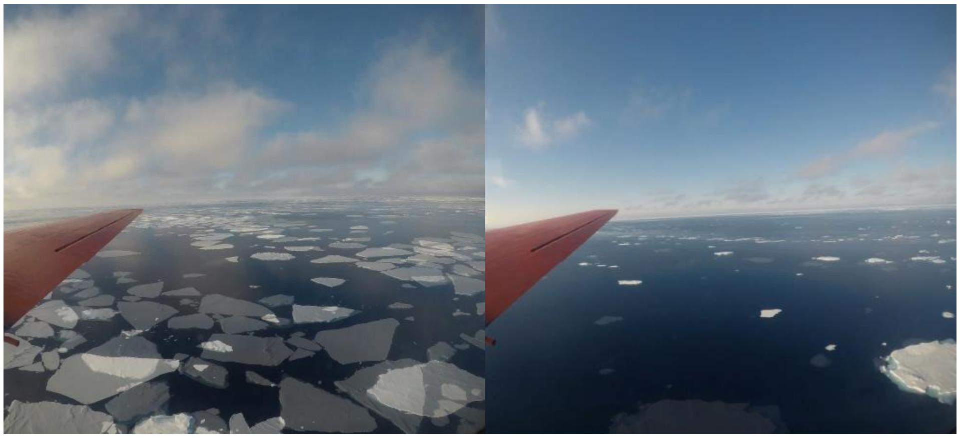

Figure 4: Broken cumulus cloud situations on 08 April 2019 during the low-level leg between 11:15 and 11:35. (Figure not included in the manuscript)

To avoid this partly misleading discussion, we omitted the term "cloud-free mode" in the revised manuscript. Instead we wrote: "**For AFLUX (Fig. 7d), mode 1 over open ocean shows a remarkably positive $\boldsymbol{CRE_{\mathrm{sol}}}$ with a median of 20 W m^{-2} for an equivalent LWP of less than 5 g m^{-2}. This solar warming effect is due to broken cumulus clouds, which often enhance $\boldsymbol{F^{\downarrow}_{\mathrm{sol}}}$ compared to a cloud-free situation for several minutes by scattering additional solar radiation towards the surface (cloud enhancement, Mol et al., 2023). Broken clouds frequently occur during cold air outbreaks over open ocean, when the cold air advected over the warm ocean reduces the thermodynamic stability and leads to the formation of cloud streets (e.g., Brümmer, 1996**[, https://doi.org/10.1007/BF00119014]**). Thus, mode 1 combines cloud-free situations with broken cloud observations, the latter producing a low retrieved equivalent LWP that is indistinguishable from cloud-free conditions.**"

Line 71: Awkward wording. Maybe "Fewer efforts have focused on CRE over open…"

Yes, we agree that this wording could be improved. Actually, we wanted to state that "**Less attention has been paid to the CRE over open (ice-free) ocean…**" and changed it accordingly in the revised version of the manuscript.

Line 105: It might be better to show Eq (1) using terms for both TIR and solar separately to make cross-referencing like this more clear.

Since we introduced the symbols in the new equations 1–4 (see answer to your earlier comment on that), we are now able to use them here and rearrange the text as follows: "**During the low-level sections, the broadband irradiances $\boldsymbol{F^{\downarrow}_{\mathrm{sol}}}$ and $\boldsymbol{F^{\uparrow}_{\mathrm{sol}}}$ on the one hand, and $\boldsymbol{F^{\downarrow}_{\mathrm{TIR}}}$ and $\boldsymbol{F^{\uparrow}_{\mathrm{TIR}}}$ on the other hand were measured by pairs of upward- and downward-directed pyranometers (sensitive in the solar range between 0.2–3.6 µm) and pyrgeometers (sensitive in the TIR range between 4.5–42 µm) at a frequency of 20 Hz.** [comment below] **From the broadband irradiance measurements, $\boldsymbol{F_{\mathrm{net,sol,cld}}}$ and**

$F_{\mathrm{net,TIR,cld}}$ (Eqs. 1 and 2), and the surface albedo (ratio of $F_{\mathrm{sol}}^{\uparrow}$ and $F_{\mathrm{sol}}^{\downarrow}$) in mostly cloudy conditions were derived."

Line 105/111: This seems deceptive. What is the response time of the thermopiles? Are you really making independent samples at 20 Hz?

Line 107: While discarding tilted data is one approach, even at 5 deg biases can be large. Corrections are possible up to 10 deg (https://www.doi.org/10.2174/1874282301004010078). Did you consider this?

Note that this answer refers to the previous two comments:

Unfortunately, we forgot to mention a couple of facts regarding the processing of our data, which we of course did in advance and which is described in detail in two other papers (Ehrlich et al., 2019; Mech et al., 2022).

It is correct that, due to the response time of the thermopiles (in the order of few seconds), the recorded 20 Hz data is not independent. We applied a deconvolution method to partly reconstruct the high frequency variability in the data and to correct the temporal shift of the time series induced by the sensor inertia (see Ehrlich and Wendisch, 2015, https://doi.org/10.5194/amt-8-3671-2015). This correction requires smoothing of instrument noise and, therefore, still does not provide independent 20 Hz data. Nevertheless, fluctuations can be resolved up to about 2 seconds, which is still below the response time of the thermopiles.

We also corrected the solar downward irradiance for aircraft attitude. Compared to the suggested reference (Long et al., 2010), we don't have separate measurements of the direct and diffuse components. Thus, we chose an intermediate way. We roughly divided the data set into sections with cloudy (dominated by diffuse radiation) and cloud-free (dominated by direct radiation) conditions and applied a correction to the latter based on cloud-free radiative transfer simulation of the direct and diffuse fractions. Since this is of course less accurate than the method of Long et al. (2010), we additionally discarded data with roll/pitch angles exceeding 5°.

Together with the two references (Ehrlich and Wendisch, 2015; Bannehr and Schwiesow, 1993), the following passage, which is added to the text, should make this clear: "**… and recorded at a frequency of 20 Hz. An inertia correction was applied, which enables to resolve fluctuations in the order of 2 s and to remove the inertia-induced time shift of the time series (Ehrlich and Wendisch, 2015). Furthermore, the impact of the aircraft attitude on $F_{\mathrm{sol}}^{\downarrow}$ was accounted for by a common correction method (Bannehr and Schwiesow, 1993). Because of remaining uncertainties in the estimation of the fraction of direct solar irradiance, the irradiance data for aircraft attitudes exceeding 5° in roll and pitch angle were discarded.**"

Line 172: meidan -> median

Changed.

3.1: Here again, I think it would be useful consider Eq (1) as LW and SW separately and to distinguish more clearly in this paragraph the methodologies used for the two bands.

Similar to the comment on line 105, we now use the symbols in the text. We started with: "**Section 2.1 describes the (mostly cloudy) measurements of $\boldsymbol{F}_{\mathbf{net,sol,cld}}$ and $\boldsymbol{F}_{\mathbf{net,TIR,cld}}$. To calculate both $\boldsymbol{CRE}_{\mathbf{sol}}$ and $\boldsymbol{CRE}_{\mathbf{TIR}}$ (Eqs. 3 and 4), $\boldsymbol{F}_{\mathbf{net,sol,cf}}$ and $\boldsymbol{F}_{\mathbf{net,TIR,cf}}$, need to be simulated.**"

To highlight, which input is used for the simulations of both $F_{\mathrm{net,sol,cf}}$ and $F_{\mathrm{net,TIR,cf}}$, we added "**For both spectral ranges…**". When it comes to the differences between the solar and the TIR ranges, we tried to separate more clearly, which input is needed for which range: "**In addition to these** (the common) **settings, $\boldsymbol{F}_{\mathbf{net,TIR,cf}}$ was simulated using a surface emissivity of 0.99 … Instead of the surface emissivity, the simulation of $\boldsymbol{F}_{\mathbf{net,sol,cf}}$ additionally requires the SZA and the definition of the local surface albedo … From the simulations, the direct/diffuse fraction of $\boldsymbol{F}^{\downarrow}_{\mathbf{sol}}$ was obtained for cloud-free conditions.**"

Figure 4: Maybe specify in the caption that this is simulated, not observed.

Yes, that makes total sense to not confuse the reader. We added "**Simulations of the …**" at the beginning of the figure caption for both (a) and (b).

Figure 8: So just to be clear, there were no clear-sky samples made during MOSAiC-ACA? I think it might be helpful to emphasize that point because to look at Figure 8 it appears as if you are reporting CRE > 25 Wm2 under clear skies.

We agree that the two modes in the distributions of MOSAiC-ACA could cause confusion if they are compared to the cloud-free and cloudy modes found for the other campaigns.

In the original manuscript, we mentioned that the two-mode structure of cloudy and cloud-free mode is only present for AFLUX and ACLOUD: "**Independent of the underlying surface type, the distributions of $\boldsymbol{CRE}_{\mathbf{TIR}}$ during AFLUX (Figs. 8a, 8d) and ACLOUD (Figs. 8b, 8e) reveal two distinct modes. Similar to the $\boldsymbol{CRE}_{\mathbf{sol}}$, the mode located around 0 W m^{-2} represents cloud-free conditions, while the second mode clearly indicates the warming effect of the clouds in the TIR range.**"

Later, when discussing MOSAiC-ACA, we explain that none of the modes represents actual cloud-free conditions (as we did before when discussing the solar CRE). We slightly adjusted the text to be more clear: "**Due to the lack of cloud-free observations, the mode with the smallest $\boldsymbol{CRE}_{\mathbf{TIR}}$ represents the broken cloud conditions (around 25 W m^{-2}).**"

To also emphasize this fact when only looking at Fig. 8, we decided to add the following sentences to the figure caption: "**Note that, due to a lack of the corresponding observations, none of the modes in (c) represents actual cloud-free conditions. The thinnest clouds, however, revealed an equivalent LWP < 5 g m^{-2} and did, thus, not contribute to the statistics shown in (f).**"