Replies to comments of Review #2

We would like to thank the reviewers for their positive and constructive feedback and appreciate their time for extensively reading and commenting on the submitted 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.

Beyond edits related to the reviews, we applied additional revisions to some text passages after carefully going through the manuscript. For these changes, we refer to the track changes file.

General

Airborne radiation measurements over the Arctic marginal sea ice zone and open ocean near Svalbard are analyzed to investigate the dependence of the cloud radiative effect on solar zenith angle, cloud optical thickness and surface albedo. It is found that the latter has by far the largest effect.

The manuscript is in all parts very well written, it is clearly organized and the topic is of large scientific interest for climate research. The paper addresses one of the most uncertain factors in climate projections, namely the impact of clouds on the surface energy budget. The analysis helps to better understand the complex interaction processes between clouds and the surface due to their effects on radiation. Most of the text can be well understood but I suggest adding some explanations for non-experts. Altogether, these suggestions and some further hints to the text are all minor points and I recommend the publication of this very well done work after revision.

Revisions

1. *I think, the description around Figure 4 (Caption and corresponding text) can be improved. The meaning of the black dashed line is somehow unclear to me. I guess the red numbers refer to the full change of the Solar CRE between the Open Ocean state and the Sea Ice state rather than to the change from the Ocean state to the intersection point. But this does not become clear. I did not fully understand the meaning of the evaluation point. Following the given numbers (131.6+0.6 = 132.2, 8.3+124.0=132.3, 127.9+4.3=132.2) the way how we come from the open ocean state to the sea ice state plays no role. This should be stressed, if correct.*

To better understand the following discussion, we also refer to the reply on the next general comment. The two terms on the right-hand side of Eq. 13 are the partial CRE differences, which result from only changing one variable between the two states, while the other variable is kept constant. Eventually, these partial CRE differences should correspond to the absolute contributions of cloud optical thickness τ and surface albedo α to the given CRE difference (132.2 W m^{-2}). Since the partial CRE differences are not constant (as indicated by the coloured numbers in Fig. 4 of the manuscript), the procedure described in Sect. 4.1 identifies a pair of values $(\alpha_{\mathrm{e}}, \tau_{\mathrm{e}})$ that is referred to as evaluation point and assures that the two partial CRE differences exactly add up to the CRE difference. As the reviewer observed correctly, there are multiple possibilities to compose the CRE difference. I. a., either changing the surface albedo first (partial CRE change of 131.6 W m^{-2}) and the cloud optical thickness second (0.6 W m^{-2}), or vice versa (8.3 W m^{-2} for the cloud optical thickness change and 124.0 W m^{-2} for the surface albedo change). However, both cases reveal different relative contributions of the partial CRE differences to the total CRE difference. The surface albedo change covers 99.5 % of the total CRE change in the first case, but only 93.7 % in the second case. Further possible solutions are distributed along the black dashed line in Fig. 4 of the manuscript. This multitude of solutions is caused because Eq. 13 is underconstrained. To obtain a single solution, we introduced the second criterion, which requires the evaluation point to lie on the connection line between both states. The intersection of this connection line and the black dashed line is representatively located in the middle between both states and constitutes the evaluation point. At this evaluation point, the partial CRE changes correspond to the red numbers, which, as all partial CRE changes, account for the full change of one driver between the two states, while the other is constant at its value of the evaluation point. The obtained numbers (127.9 W m^{-2} and 4.3 W m^{-2}) correspond to the absolute contributions of surface albedo and cloud optical thickness to the CRE change.

The modified text contains a clearer description of Fig. 4 and the associated method. To more easily refer to the median values of τ and α for the open ocean and sea ice states as well as the corresponding differences, we first assign the symbols τ_1, α_1, τ_2, and α_2 to the median values: **"… τ_1 = 8.5 and α_1 = 0.10 over open ocean … and τ_2 = 7.0 and α_2 = 0.78 over sea ice …"** (lines 221–222). Subsequently, we revised Sect. 4.1 starting from its second paragraph:

"The decomposition of $\Delta\mathrm{CRE}$ into partial CRE differences that only account for a change in τ or α between the two states is given by:

$$\Delta\mathrm{CRE} = \Delta\mathrm{CRE}_{\Delta\tau}(\alpha) + \Delta\mathrm{CRE}_{\Delta\alpha}(\tau), \quad (13)$$

which is equivalent to integrating Eq. 10 between the states. For example, the partial CRE difference $\Delta\mathrm{CRE}_{\Delta\tau}(\alpha)$ represents the CRE contrast resulting from a change $\Delta\tau$ from τ_1 to τ_2 at any constant α. Due to the non-linear sensitivity of the CRE to both τ and α, $\Delta\mathrm{CRE}_{\Delta\tau}(\alpha)$ and $\Delta\mathrm{CRE}_{\Delta\alpha}(\tau)$ depend on the concrete value that α and τ, respectively, are fixed to. These non-linearities are indicated by the pairs of green and blue numbers in Fig. 4. Despite an identical $\Delta\tau$, the associated $\Delta\mathrm{CRE}_{\Delta\tau}$ is 8.3 W m^{-2} if α corresponds to α_1, but only 0.6 W m^{-2} for α_2. Similarly, $\Delta\mathrm{CRE}_{\Delta\alpha}$ amounts to 131.6 W m^{-2} if $\tau = \tau_1$ and 124.0 W m^{-2} for $\tau = \tau_2$. Consequently, for neither (α_1, τ_1) nor (α_2, τ_2), the partial CRE differences do exactly add up to $\Delta\mathrm{CRE}$ in Eq. 13. Therefore, the approach suggested in the following, which was not considered by the APRP method (Taylor et al. 2007), identifies the values α_e and τ_e that precisely satisfy Eq. 13. This pair of values is referred to as evaluation point in the following.

Since Eq. 13 is underconstrained with the two unknown variables α and τ, the possible solutions to it are distributed along the black dashed line in Fig. 4 and include both (α_1, τ_2) and (α_2, τ_1). However, the fraction of the partial CRE differences with respect to the total CRE difference (i. e., the relative contributions) are not identical for these solutions. To obtain a unique pair of relative contributions, an additional criterion is introduced, which requires $(\alpha_\mathrm{e}, \tau_\mathrm{e})$ to lie on the straight connection line between the two states (black solid line in Fig. 4), parameterized as

$$\binom{\tau}{\alpha} = \binom{\tau_1}{\alpha_1} + s \cdot \binom{\tau_2 - \tau_1}{\alpha_2 - \alpha_1}. \quad (14)$$

By inserting Eq. 14 into Eq. 13, this requirement yields a solution for the parameter s that is used to calculate the final evaluation point $(\alpha_{\mathrm{e}}, \tau_{\mathrm{e}})$ = (0.49, 7.7). For these values, the partial CRE differences eventually quantify the absolute contributions of cloud and surface, which amount to 4.3 W m^{-2} and 127.9 W m^{-2} (red numbers in Fig. 4) and correspond to relative contributions of 3.3 % and 96.7 %, respectively.” (lines 226–247)

The caption of Fig. 4 is updated to: **“Solar CRE parameterized with Eq. 9 as a function of τ and α. The symbols indicate the median states (α_1, τ_1) over open ocean and (α_2, τ_2) over sea ice calculated for the case study on 4 April 2019. The blue and green numbers (all in W m^{-2}) quantify the partial solar CRE change along the respective lines. The red numbers represent the finally obtained absolute contributions of τ and α to the solar CRE difference, corresponding to the partial solar CRE differences at the evaluation point $(\alpha_{\mathrm{e}}, \tau_{\mathrm{e}})$. The evaluation point is determined by the intersection of two criteria: first, it must lie on the black solid line connecting the two states and, second, it must satisfy Eq. 13, which is the case for all (α, τ) along the black dashed line. See text for more details.”**

2. *Perhaps, a Discussion section could be added where, e.g. the differences between both methods based on equations (10) and (13) are discussed and their different ranges of validity. In this connection Lines 195-210: Is it possible to give a threshold for the validity of (10)? Further possible points for a discussion is the difference to mid latitudes and if the results have any effects on or benefits for modelling.*

Although we decided not to add a dedicated Discussion section to our manuscript, we tried to cover the suggested discussion points in the updated version of our manuscript.

(1) <u>Differences between methods based on Eqs. 10 and 13:</u>

The first method based on Eq. 10 expresses a change of the CRE by means of the total differential, with

$$\mathrm{dCRE} = \frac{\partial \mathrm{CRE}}{\partial \tau}(\tau, \alpha) \cdot \mathrm{d}\tau + \frac{\partial \mathrm{CRE}}{\partial \alpha}(\tau, \alpha) \cdot \mathrm{d}\alpha,$$

where the contributions of cloud optical thickness τ and surface albedo α are given by the respective terms on the right-hand side. However, due to the assumption of infinitesimal differences dCRE, $\mathrm{d}\tau$, and $\mathrm{d}\alpha$, the applicability of this method is limited. Actual measured or modelled samples are a discrete collection of data points with ideally small, finite differences $\delta\mathrm{CRE}$, $\delta\tau$, and $\delta\alpha$ between two adjacent points, such that a more accurate formulation of the above equation would be:

$$\delta\mathrm{CRE} = \frac{\partial \mathrm{CRE}}{\partial \tau}(\tau, \alpha) \cdot \delta\tau + \frac{\partial \mathrm{CRE}}{\partial \alpha}(\tau, \alpha) \cdot \delta\alpha + \mathrm{Res}.$$

The finite differences in combination with the non-linear dependence of the CRE on α and τ (see also Fig. A1 in the manuscript) lead to differences of the sensitivity coefficients $\frac{\partial \mathrm{CRE}}{\partial \tau}$ and $\frac{\partial \mathrm{CRE}}{\partial \alpha}$ between the two neighbouring data points, resulting in the residual term Res. For sufficiently small $\delta\mathrm{CRE}$, $\delta\tau$, and $\delta\alpha$, these sensitivity differences and the residual are minor. The example time series in Fig. 3 of the manuscript has a sampling frequency of 20 seconds and reveals a negligible residual of around 10^{-6} W m^{-2} s^{-1} compared to the CRE change in the order of 0.5 W m^{-2} s^{-1}. Therefore, we omit the residual and work with the differential equation in the manuscript. However, coarsening the resolution of the time series to minutely values increases the residual to roughly 0.1 W m^{-2} s^{-1}, which corresponds to 10–20 % of the CRE change and highlights the limits of the method. Note that the resolution of a data set is less crucial than the differences of the sensitivities between adjacent data points. Therefore, the validity of the method using Eq. 10 should be evaluated based on the variability of the sensitivities and the impact of the residual rather than a fixed threshold. Furthermore, just like the example time series, the analysis of data with significant small-scale variability might benefit from a carefully chosen smoothing to reduce the point-to-point differences.

For cases, where the first method is not suitable due to a significant residual, we propose the second method. A given CRE difference $\Delta\mathrm{CRE}$ between two points (the symbol Δ indicates a too large difference to reliably apply Eq. 10) can be obtained by integrating the total differential:

$$\int_{\mathrm{CRE}_1}^{\mathrm{CRE}_2} \mathrm{dCRE} = \int_{\tau_1}^{\tau_2} \frac{\partial\mathrm{CRE}}{\partial\tau}(\tau,\alpha)\cdot \mathrm{d}\tau + \int_{\alpha_1}^{\alpha_2} \frac{\partial\mathrm{CRE}}{\partial\alpha}(\tau,\alpha)\cdot \mathrm{d}\alpha,$$

where the subscripts 1 and 2 describe the two data points. This integration is equivalent to Eq. 13:

$$\Delta\mathrm{CRE} = \Delta\mathrm{CRE}_{\Delta\tau}(\alpha) + \Delta\mathrm{CRE}_{\Delta\alpha}(\tau)\ [+\ \mathrm{Res}].$$

However, depending on the exact values used for α and τ, there might still be a residual, which is removed by the procedure described in Sect. 4 of the manuscript (see also discussion on comment above). Since this method is applicable to any difference of τ and α between two points, it is also suitable to partition a CRE difference between two arbitrary states into its contributions. These states, which may even be averages of multiple data points, can be different points in time and location or the results of two simulations with different input. Although it would be possible to compare two adjacent points of a data series using Eq. 13, the method based on Eq. 10 is sufficient in most cases.

In the manuscript, we considered the above discussion as follows: To better prepare the reader for the discussion, we slightly revised the beginning of Sect. 3.2:

"For continuous observations with weak differences of the drivers between neighbouring data points, the total differential of Eq. 9 (neglecting the SZA dependence), with

$$\mathrm{dCRE} = S_\tau(\tau,\alpha)\cdot \mathrm{d}\tau + S_\alpha(\tau,\alpha)\cdot \mathrm{d}\alpha, \quad (10)$$

yields an accurate result for the corresponding change of the CRE. The terms on the right-hand side of Eq. 10 represent the absolute contributions of τ and α to the CRE change, which are determined by both the sensitivities of the CRE with respect to τ (S_τ) and α (S_α) and the absolute change of these parameters ($\mathrm{d}\tau$ and $\mathrm{d}\alpha$). The sensitivity coefficients, given by

$S_\tau(\tau,\alpha) = \frac{\partial\mathrm{CRE}}{\partial\tau}$ **and**

$S_\alpha(\tau,\alpha) = \frac{\partial\mathrm{CRE}}{\partial\alpha}$**,**

both depend on τ and α and are discussed in detail in Appendix A. Along the flight leg of the example case, the results of the separated contributions are shown in Fig. 3. The temporal changes of the absolute contributions of τ and α are illustrated in Fig. 3c and indicate their respective tendency to the CRE transition." (lines 173–183)

The main discussion on the difference between the methods is added to the beginning of Sect. 4:

"Due to the assumption of infinitesimal differences in Eq. 10, the approach described in Sect. 3.2 may lead to significant uncertainties if the differences of τ and α between two data points become too large. This is particularly the case, when the non-constant sensitivity coefficients S_τ and S_α (see Appendix A) vary significantly between the two points, causing a considerable discrepancy between the CRE change (left-hand side of Eq. 10) and the sum of the absolute contributions (right-hand side of Eq. 10). In this case, another method, which is proposed in the following and applicable to any point-to-point difference, may be considered. This method is likewise suitable for disentangling the contributions of the drivers to a CRE change between two isolated states, such as different points in time or location." (lines 205–211)

Furthermore, we added the following sentences to the Conclusions section:

"Since the method using the total differential can lead to significant uncertainties for too large changes of the drivers, an alternative approach to disentangle their contributions was introduced. This decomposition method is similar to the approximate partial radiative perturbation technique (Taylor et al., 2007) and also applicable to partition the CRE difference between two distinct states into the contributions of the drivers." (lines 287–290)

(2) <u>Difference to mid-latitudes</u>

Since our method is based on a physical relationship between the CRE and the drivers, the method itself is not restricted to the Arctic. However, the relative contributions of the drivers to a CRE change likely differ between the polar regions and the mid-latitudes, e. g., due to less severe surface albedo differences. To account for this discussion, we added a corresponding sentence as an outlook to the Conclusions section:

"The general approach used in this study is not limited to the Arctic. Since the method is universally applicable to quantify the contributions of drivers to any given CRE difference, it could also be used to assess how the importance of certain drivers differs, e. g., between the polar regions and the mid-latitudes, where surface albedo contrasts are usually weaker." (lines 299–302)

(3) <u>Effects on models</u>

The method described in Sect. 4 of the manuscript may furthermore help to interpret potential biases of the CRE between simulations and observations. Decomposing the CRE differences quantifies the individual contributions of the drivers to the bias. The results will inform about, which model parameters cause the largest CRE uncertainty and require the most crucial accuracy.

We add the following sentence to the conclusion section: **"Furthermore, modelling could possibly benefit from quantifying the contributions of the drivers to a potential CRE bias, which can help to evaluate for which parameters an accurate representation in the model is most crucial."** (lines 302–304)

Hints for text improvement

Lines 10-12: at this point it is perhaps unclear how non-cloud conditions can dominate the cloud radiative effect.

We agree that the dominance of the non-cloud properties for CRE differences might be difficult to understand here, although we mentioned before (line 6-7) that the CRE is also affected by solar zenith angle and surface albedo. However, we won't be able to give a full explanation of the relationship between CRE and non-cloud properties already in the abstract and simply stated what we found in the study. Nevertheless, we attempted to clarify the dominating impact of the non-cloud properties by rewriting the last sentence of the abstract as follows:

"Using the same approach, the analysis is extended to observations from a series of aircraft campaigns and indicates that the variability of the non-cloud properties SZA and surface albedo between seasons and surface types, respectively, has a larger impact on the resulting difference of the solar CRE than the variability of cloud properties." (lines 8–11)

Line 22: define a larger/smaller REB

We see that the meaning of a larger/smaller REB might be unclear at this point as we haven't introduced the corresponding equations yet. To avoid confusion, we skipped "a larger REB" at this point but kept the resulting surface warming as the most important statement. The updated sentence reads:

"On the one hand, the darker open ocean directly affects the solar REB by increasing the absorption of solar radiation, which leads to an intensified surface warming…" (lines 21–22)

Line 41: a negative CRE change is a decrease of the CRE?

Correct. We added **"…, i. e., decreasing CRE, …"** (line 40)

Line 52: better: solar cooling effect caused by clouds over open ocean?

We used the formulation **"cooling effect of clouds over open ocean"** (lines 52–53).

Line 67: unclear: which parameters?

We agree that the connection to the cloud, surface, and thermodynamic parameters mentioned in the previous sentence, where they are called **"conditions"**, is not obvious. To be consistent, we changed the term **"conditions"** to **"properties"** (line 59) and likewise replace the confusing **"parameters"** by **"considered properties"** (line 61).

Line 105: why is the index of the transmissivity of cloud free atmosphere 'atm' and not 'cf' ?

The subscript "cld" does not account for the transmissivity of the entire cloudy atmosphere, but only to the cloud itself. The transmissivity of the atmosphere, but without the cloud, still affects the irradiance in cloudy conditions (see Eq. 9 in the manuscript). This is in contrast to the "cld" and "cf" net irradiances, which result from interactions of radiation with cloudy (clouds as well as water vapour, aerosols, ...) and cloud-free (only water vapour, aerosols, ...) atmosphere, respectively. In this way, the subscript "cld" can serve as an addition to "atm" for the transmissivity rather than a counterpart. Therefore, we decided to keep the subscript "atm". Instead, we replace the phrase **"... the transmissivities of cloud $\mathcal{T}_{\mathrm{cld}}$ and cloud-free atmosphere $\mathcal{T}_{\mathrm{atm}}$ ..."**, which might have led to confusion, by the hopefully clearer phrase **"... the broadband transmissivities of cloud $\mathcal{T}_{\mathrm{cld}}$ and atmosphere (excluding clouds) $\mathcal{T}_{\mathrm{atm}}$ ..."** (lines 111–112).

*Line 111: function **of** alpha and mu*

Correct. Thanks for noticing. However, we changed the formulation of the sentence such that this word group does not occur anymore.

Line 143: better transition of the CRE from ... to ...

We added **"..., e. g., from open ocean to sea ice, ..."** (line 151–152)

Caption figure 3: the caption text should better fit to what is used in the figure, so either you use abbreviation mu, tau alpha or the complete names. Also, please add the day to which these observations belong.

Based on a comment of the other reviewer, we added the symbols μ, τ, and α to the axis labels and the legend in Fig. 3a, which improves the connection between the figure and the caption. Furthermore, we changed the line style of the yellow, green, and blue lines to be independent of the colour coding and coloured the background of panel (d) to indicate the dominant driver of the CRE transition. The updated version of this figure is shown in Figure 1 of these replies. Additionally, we mentioned the day by adding **"...** flight leg **performed on 4 April 2019"** to the end of the first sentence of the figure caption.

Line 195: better: two states defined by different values of optical thickness, surface albedo etc.

Due to a revision of the introduction to Sect. 4, the sentence concerned no longer occurs in the updated manuscript (please also see the discussion on the first point of the second general comment).

Line 195: without correlation means here simply large differences between the states?

Yes, basically that is what we wanted to express. For too large differences of τ and α between adjacent data points, the method based on Eq. 10 is not suitable. Please see the discussion on the first point of the second general comment for more details and the implemented text revisions.

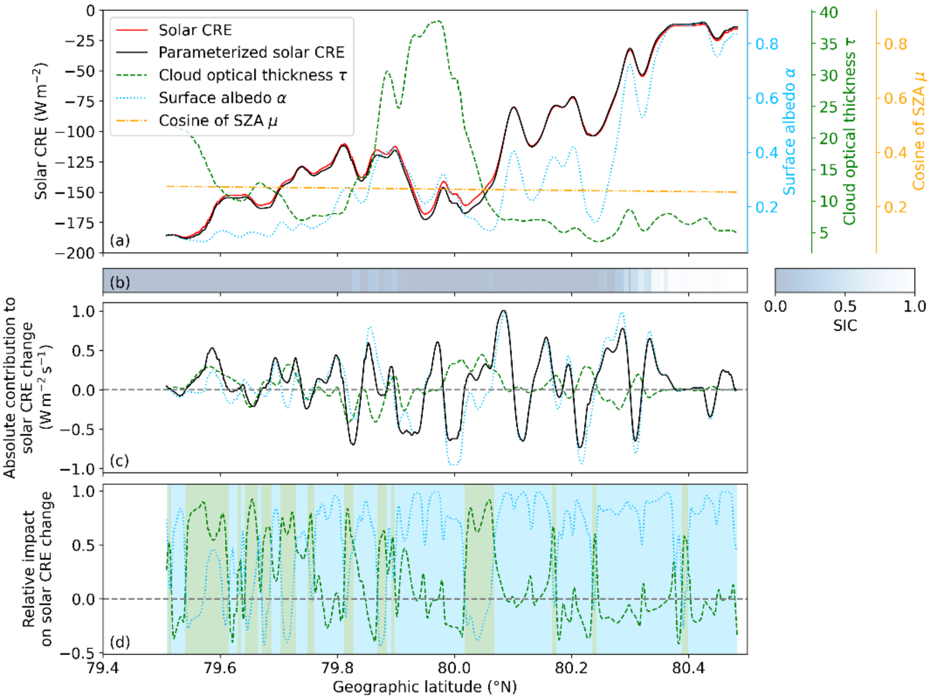

Figure 1: Updated version of the manuscript's Fig. 3: We added the symbols μ, τ, and α to the axis labels and the legend in panel (a) and applied a colour coding to panel (d) to indicate the dominant driver of the CRE (green: cloud optical thickness dominant, blue: surface albedo dominant).

Please increase the thickness of the green line in the figure.

We agree that especially the green lines are badly visible. To be consistent, we thickened all lines. Additionally, we framed the coloured numbers for better contrast (especially for the number 4.3). The updated Fig. 4 of the manuscript is shown in Figure 2 of this document.

Line 215: perhaps better: see the pairs of green blue and red numbers ....

After rewriting the corresponding section, the phrase **"pairs of green and blue numbers in Fig. 4"** now occurs in line 232.

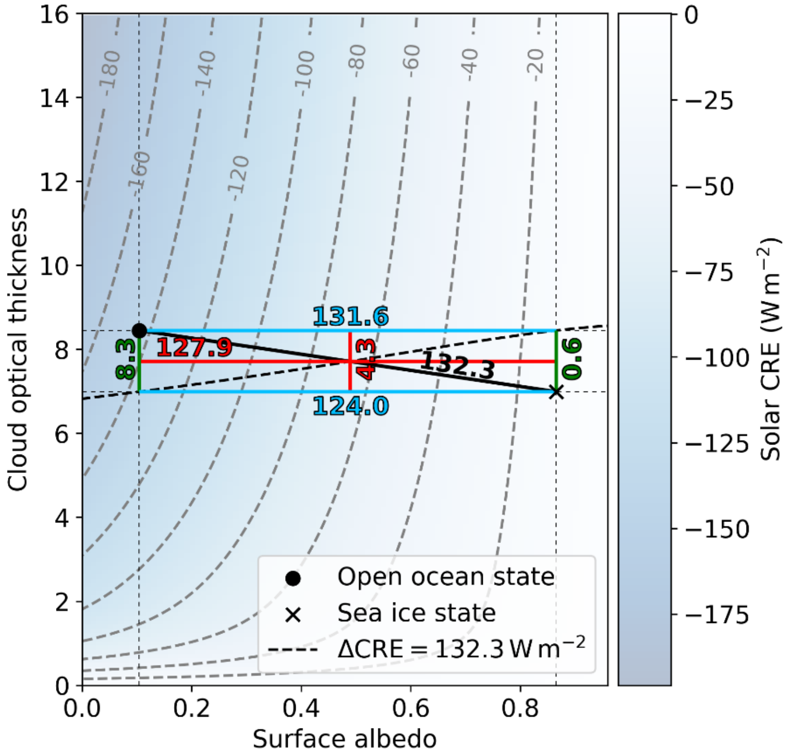

Figure 2: Updated version of the manuscript's Figure 4 with thicker green, blue, and red lines