Reply to Referee #1

(Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-534)

We would like to thank the reviewer for her or his time and the beneficial comments, which will help to improve the manuscript. Please find the replies to the referee comments below. The page and line numbers given by the referee relate to the manuscript in discussion, the numbers in our reply to the revised manuscript.

Referee comments are highlighted in **bold**, *changes* in the manuscript in *italic*.

Main criticisms of this paper:
1) Additional referencing of the literature is needed to put the paper into context and understand what is novel in this work.
2) An uncertainty analysis is needed.
3) Some of the writing is confusing and needs to be edited for clarity.
4) There are gaps in the descriptions of the measurements and methods that make the work difficult to understand or reproduce.
These points are discussed in the detailed comments below.

Title: The title should be reworded. Perhaps something like, "Cloud radiative forcing at the Arctic springtime marginal sea ice zone derived using low-level airborne observations."
The title proposed by the reviewer would implicate that we analyze/characterize the CRF during the ACLOUD campaign and analyze e.g. its dependence on surface and cloud properties. However this is not the primary intension of the manuscript and will be done in more details in an upcoming paper. Instead, the manuscript aims to discuss and refine the methods used to derive the CRF. In particular, we show the importance of the clear sky albedo estimate for the estimate of CRF, for which in fact we need observations to show the impact. However, we acknowledge that the focus of the work was not made clear. We changed the title to:

"Reassessment of shortwave surface cloud radiative forcing in the Arctic: Consideration of surface albedo-cloud interactions"

Language (overall): The authors should go through the paper and make sure every paragraph makes a single, clear point. They should also go through each sentence and make sure that it is correct, comprehensible, and stated as simply as possible. I suggest asking a colleague to read the paper and then working with them on how to clarify anything that they do not understand.
We apologize that our writing was confusing and restated/edited a couple of sections. Please see the marked-up manuscript for details.

Abstract lines 1 and 2: "warming or cooling effect . . . on the radiative energy budget."Clouds do not cool the energy budget. Please restate.
We have changed the first two sentences in the abstract accordingly to:

"The concept of cloud radiative forcing (CRF) is commonly applied to quantify the impact of clouds on the surface radiative energy budget (REB). In the Arctic, radiative interactions between microphysical and macrophysical properties of clouds and the surface modify the warming or cooling effect of clouds, complicating the estimate of CRF obtained from observations or models."

First paragraph of the introduction: This paragraph is difficult to understand, has a lot of unnecessarily detail, and only provides general motivation. I think a few sentences can explain that clouds are important for the Arctic. What is really needed prior to the second paragraph is more specific motivation for this work, including why estimates of CRF and REB are important and how they are used and calculated in the literature (discussed more below).

We agree, that the focus of the introduction did not fit perfectly the motivation of the study. Therefore, we changed the introduction to be more specific on the general estimate of CRF. In addition, we added a literature overview in the new section 3.1 "Common approaches" describing the state of the art methods to calculate the CRF.
Furthermore we restated the sentence about the cloud feedback (more specifically cloud radiative feedback) to (p.2 l.2):
"One prominent example is the cloud radiative feedback, which includes the effects of an increasing cloud amount in the Arctic, balancing between potential increase of both longwave downward radiation (positive) and cloud top reflectivity (negative)."

Page 2 lines 18-22: these sentences are a distraction from the rest of the paragraph, which focuses on SZA and albedo.
We completely changed this section. (See marked-up manuscript)

When the words heterogeneous or heterogeneity are used, the authors need to state what is varying – for heterogeneous sea ice is it type of ice? Or ice fraction? What is meant by heterogeneous albedo?
The reviewer is right, we should have been more specific. We intended to say "fluctuations of albedo in space scale", or "heterogeneous albedo fields". This heterogeneity is caused by sea ice concentration, patches of snow on bare sea ice etc. We reworded the sections, where it was unclear or misleading and used the two extended phrases "fluctuations of albedo", or "albedo fields".

Abstract and Introduction: Is the most important result the application of the parametrization of Gardner and Sharp (2010) to measurements? If this is the case, this should be clear in the abstract and introduction. For example, the authors state in the introduction that, "Both processes have been parametrized, for example by Gardner and Sharp (2010) based on simulations, however, their impact on estimates of the CRF in the Arctic have not yet been evaluated." They should go on to state in the following paragraph that they apply these parametrizations in this work.

The reviewer is right that we should have emphasized the importance of the Gardner and Sharp (2010) parameterization more clearly, which enables to reproduce the clear sky albedo from the cloudy observations. We added in the abstract:

"A method to consider this surface albedo effect by continuously retrieving the cloud-free surface albedo from observations under cloudy conditions is proposed, <u>using an available snow and ice albedo parameterization.</u>"

As well we modified the last paragraph in the introduction to make the outcome/structure of the study more clear:

"In section 4 a method is introduced to retrieve the shortwave surface albedo in the hypothetical cloud-free atmosphere from measurements under cloudy conditions, by using an available snow and ice albedo

parameterization from Gardner and Sharp (2010) and a shortwave transmissivity-based retrieval of cloud liquid water path (Appendix A)."

Introduction: Although the paper has a long reference list, missing are examples from the literature of calculations of CRF and radiative fluxes based on observations in the Arctic. Context of the literature is also needed to show what ideas or parametrizations are novel here. For example, if Eqs (7) and (8) are novel, please make that clear in the introduction as well as in Sect. 3, as well as how they relate to calculations of CRF in the literature. The authors should explain how CRF is used in such studies, what are the shortcomings, and how their work addresses these shortcomings.

We extended the introduction by a section discussing the general conclusions from available studies (p.2 l.14).

"Long-term ground-based observations of CRF in the Arctic (Walsh and Chapman, 1998; Shupe and Intrieri, 2004; Dong et al., 2010; Miller et al., 2015) showed that in the longwave wavelength range clouds tend to warm the surface. The magnitude of the warming is influenced by macrophysical and microphysical cloud properties (e.g., Shupe and Intrieri, 2004) and by regional characteristics (Miller et al., 2015) and climate change (Cox et al., 2015). In the solar spectral range, clouds rather cool, whereby the strength and timing over the year is determined, besides cloud microphysical properties, by the solar zenith angle (SZA) and the seasonal cycle of surface albedo (e.g., Intrieri et al., 2002; Dong et al., 2010; Miller et al., 2015). However, the required cloud-free reference (Fnet;cf) poses a serious problem to all observations in the cloudy Arctic (Shupe et al., 2011), as the unknown thermodynamic and surface albedo conditions in cloud-free environments is modified by the presence of clouds itself."

In addition, we added a more detailed literature overview in the new section 3.1 "Common approaches", where a discussion of the available approaches is given (please see the new manuscript). This section aims to identify shortcomings of the common approaches such as the representations of cloud-free albedo.

Measurements: More information is needed about the measurements. What wavelengths are used? Presumably the aircraft had both up-looking and down-looking pyrgeometer and pyranometers?
In section 2.2 we referred to two papers Wendisch et al. (2019) and Ehrlich et al. (2019b). These papers give a detailed overview of the campaign (Wendisch et al., 2019) and instrumentation (Ehrlich et al., 2019b), where all required information is provided. They extensively describe the campaign, the flights, the instrumentation, wing-by-wing comparison and necessary processing. However, to make it easier for the reader we added some general specifications of the broadband radiatiometer in the revised manuscript (p.4 l.3).

"In this paper, shortwave and longwave, upward and downward broadband irradiance have been analyzed from measurements with a frequency of 20 Hz obtained from two sets of Pyranometer (0.2-3.6 µm) and Pyrgeometer (4.5-42 µm). From 5 these irradiance data the net irradiance and surface albedo have been derived."

(Also, please use "longwave" and "shortwave" instead of "terrestrial" and "solar."

We have changed the wording, equations, subscripts and labels in the figures.

The text refers to the cloudy ABL, but I think data are only used where the cloud was above the aircraft? (E.g. all upwelling flux measurements were for clear skies). Please clarify this.

We apologize if the definition of CRF in the introduction with “cloudy” was misleading and we changed it to “all-sky”. However, as stated in Ramanathan et al. (1989), “cloudy” is not equal to overcast conditions. The low level section are not filtered for overcast conditions. All data, from overcast, broken cloud fields, and clear-sky conditions are included, as can be seen in the CRF distributions shown in Fig. 10b,c (clear-sky values around 0).

As described in section 3.2 the upward longwave fluxes cancel in the CRF equation assuming the instantaneous approach. The upward shortwave fluxes or the surface albedo are obtain in all-sky conditions and are corrected by the method described in section 4 to represent the cloud-free albedo.

How did you ensure that there was no cloud around or below the aircraft?

The average flight altitude for the low-level section was 80m, and often even below 60m. Therefore, the low-level section were always below the lowest cloud base. There have been cases with precipitation, but precipitation does influence the radiative fluxes only little. To confirm the cloud-free conditions below the aircraft , we used cameras installed in the aircraft, participated in the flights or checked the Nevzorov Probe (LWC,TWC) data (if available) for cloud particles in flight altitude. (Dataset available: https://doi.org/10.1594/PANGAEA.906658)

Please also provide more detail about measurements of atmospheric thermodynamics, and a table showing the various measurements (with time and location) as context.

During the ACLOUD campaign we obtained hundreds of in situ profiles covering the 6 weeks with 2 aircraft and dropsondes in a region north-west of Svalbard (see Fig. 1), which were merged with radiosoundings from Ny-Alesund and from the (partly moving) research vessel Polarstern during the PASCAL campaign, described in section 2.2 and 2.3. Therefore, it is hard to give a comprise overview of these data in a single table. In general, the airborne in situ profiles are distributed similar to the flight pattern shown in Fig. 1 (descending/ascending before/after each low-level section from/to lower/higher altitude). We added (p.4 l. 10):

“The local atmospheric thermodynamic state, including air temperature and relative humidity was determined by dropsondes (Ehrlich et al.,2019) and aircraft in situ observations (Hartmann et al.,_2019) <u>during ascents and descents in the vicinity of the low-level flight sections.</u>”

All details (e.g. cruise track of Polarstern) can be accessed from the cited papers Wendisch et al. (2019) and Ehrlich et al. (2019). The datasets are all available on the PANGAEA database (see data availability). Time series of vertical profiles from radiosoundings during ACLOUD/PASCAL are shown in Knudsen et al. (2018).

Finally, Page 2, line 11 implies that this work uses all-sky minus clear-sky (other definitions of CRF use cloudy-sky minus clear sky). Were all downwelling flux measurements of cloudy sky?

See reply three comments above. We used all scenes during the flight sections including overcast, broken cloud fields and clear sky.

Radiative transfer simulations: Sufficient information is needed here that the results are reproducible. What was the vertical resolution? How were the measurements (dropsonde, radiosonde, and surface) merged? What was used for concentrations of other trace gases (most notably for the longwave calculations, CO_2). It would be helpful to specify which flux and albedo terms were calculated with the various models (longwave, shortwave and 2D vs. 3D). What are the uncertainties for the radiative

transfer calculations?

We apologize that we did not fully described these technical details, which are in fact important for the reproducibility. We extended the section 2.3 to fulfill all points:

"The radiative transfer simulations for the cloud-free conditions were performed with the libRadtran package (Emde et al., 2016) using the one-dimensional, plane-parallel discrete ordinate radiative transfer solver DISORT (Stamnes et al., 1988) and the molecular absorption parameterization from Kato et al. (1999) for the shortwave spectral range (0.28–4 µm), and from Gasteiger et al. (2014) for the longwave wavelengths range (4–100 µm)."

"Hence, profiles from in situ measurements of temperature and relative humidity on board of both aircraft and, if available, dropsonde measurements from the Polar 5 aircraft were used to replace the radiosounding layers by the local atmospheric profiles."

"The atmospheric levels below flight altitude were linearly interpolated to the surface temperature observed by the KT-19 assuming an emissivity of unity. The assumption of the black-body emissivity is justified by the high spectral emissivity for nadir observations in this wavelength range (Hori et al., 2006)."

"The sub-Arctic summer profile (Anderson et al., 1986) was used to complete the profiles including gas concentrations up to 120 km altitude."

"The high vertical resolution of the in situ observations was reduced for the radiative transfer simulations to 30m below 1000m and stepwise increases to 5km at 120km altitude. The surface albedo is obtained from upward and downward looking pyranometers and a method described in section 4."

In the last paragraph of section 2.3 we clarify which radiative transfer model is used for which purpose (p.5 l18):

"Spectral surface albedo values for the sensitivity study in section 3.5 were simulated using the spectral Two-streAm Radiative TransfEr in Snow model (TARTES) (Libois et al., 2013). 3D radiative transfer simulations for the albedo smoothing kernels applied in section 3.4 and the appendix A were performed with the open-source Monte Carlo Atmospheric Radiative Transfer Simulator (MCARaTS) (Iwabuchi, 2006; Iwabuchi and Kobayashi, 2008)."

Regarding the uncertainties of radiative transfer simulations we referred to Randels et al. (2013). We added in section 3.4.1 (p.12 l.14-16):
"In addition to measurement uncertainties of the used broadband radiometer (<3 %, (Ehrlich et al., 2019b)), the radiative transfer modelling can induce a bias (<2 %) in the shortwave wavelength ranges (Randles et al., 2013)."

Section 3.2: A lot of work has been done on the longwave CRF that is relevant here. For example, Cox et al 2015 (listed above) examines temperature and humidity.

We are sorry, if the focus of this section was not made clear. This study should show, how important it is to track thermodynamic profile changes during large scale processes like warm air intrusions or cold air outbreaks, because they significantly influence the local estimate of CRF and how these processes impact

the local energy budget. We did not intend to generally explain how temperature and humidity changes downward irradiance.
We changed some sentences in this section and added specific citations to make the focus of the section more clear:
(p. 8 l. 30-31)
"As was shown by Tjernström et al. (2015, 2019) such events might significantly impact the local energy budget along the trajectory."
(p.10 l. 4-6)
"Especially for airmass transformation like warm air intrusions and cold air outbreaks in the Arctic (Pithan et al., 2018), this is a relevant issue, <u>and requires a precise representation of airmass transformations by models or local in situ observations along the trajectory."</u>

Uncertainty analysis: A variety of assumptions are made in this work and the calculations and measurements all have associated errors and uncertainties. An uncertainty analysis is needed.

In the following we try to give a realistic estimate of uncertainties based on the presented workflow, which consisted of uncertainties in the observed broadband radiation and surface albedo, the simulated radiation, the LWP equivalent retrieval and the retrieved cloud-free albedo and cloud-free net fluxes. A detailed discussion of this uncertainty analysis would blow up the manuscript significantly and distract from the main conclusions. We, therefore, did not put all the calculations in the revised manuscript but added the uncertainty estimate where it was needed.

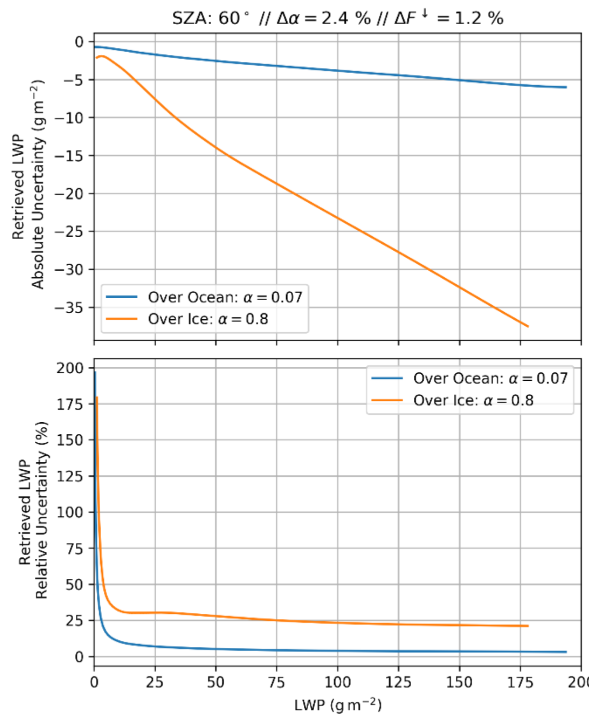

Figure 1 Absolute and relative retrieval uncertainties of equivalent LWP as a function of cloud LWP and for two surface albedos above open ocean (0.07) and sea ice/snow (0.8).

<u>Uncertainties in the LWP equivalent retrieval:</u>
To keep the uncertainties in a realistic range, we applied an deviation between the observed and simulated downward solar irradiance of 1.2 %, based on the results from the cloud-free flux closure study in section 3.4 (Figure 4 and deviations in the text). The albedo uncertainties result in 2.4 %. In Figure 1 (this document) the estimated absolute and relative uncertainties are given over ice and open ocean as a function of LWP and for a solar zenith angle of 60° (representative for ACLOUD). The theoretical observations and lookup tables for the "observed" conditions are combined in worst case scenario.
We added in the appendix (p. 23 l. 16-17):
"The relative uncertainty range of this retrieval for homogeneous clouds and surface can be expected between 15 % and 35 % over open ocean and sea ice respectively."

<u>Uncertainties in the retrieval of cloud-free albedo:</u>
In Fig. 2 (this document) synthetic distributions of LWP and Albedo are applied to the lookup tables generated using the parameterization from Gardner and Sharp (2010). The major contribution to the

uncertainties of the retrieved cloud-free albedo stems from the observed broadband albedo itself. Uncertainties from the LWP retrieval contribute only minor to errors in the cloud-free albedo. Given the uncertainty of the observed albedo of 2.4 % and the error in simulated shortwave F_down of (2 %), we conclude that the relative uncertainty of solar net fluxes (F_down_cf – alpha_cf * F_down_cf) is below 20 % above ice and lower above the open ocean and added in section 4.1.1 (p. 18 l. 32 – p.19 l.2):

"The uncertainties in the estimate alpha_cf and the shortwave F_net,cf depend mainly on the observed alpha_all, as was investigated by applying synthetic albedo and LWP distributions to the lookup tables. Due to the non-linear increase of alpha_all with LWP the potential error induced by uncertainties in the retrieved LWP is larger for lower LWP and additionally depends on the prevailing surface types. The overall uncertainty in the cloud-free shortwave net fluxes using the retrieved alpha_cf can be expected below 20% above high surface albedos, decreasing with decreasing surface albedo."

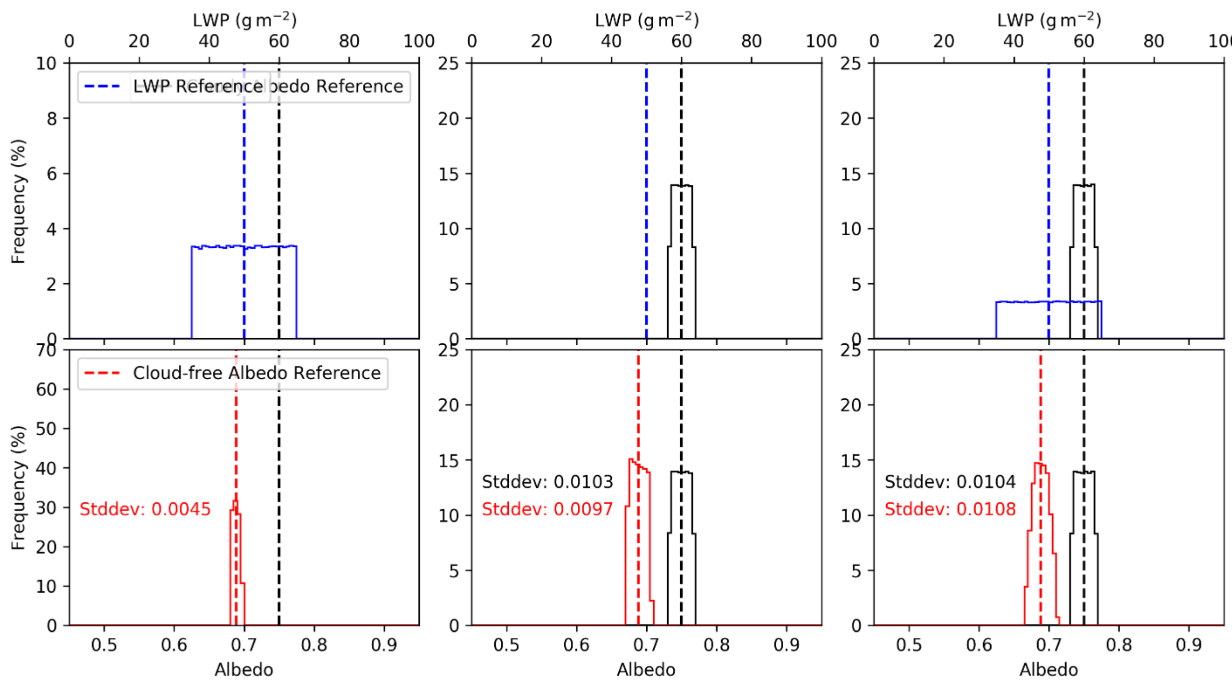

Figure 2 Upper Panels: Input for the cloud-free albedo retrieval. Lower Panels: Output of cloud-free albedo (red distribution). Albedo input in black as reference. Left panels: Only LWP uncertainty applied. Middle panels: Only albedo uncertainties applied. Right panel: LWP and Albedo uncertainties combined.

Technical details:

- I_f needs to be defined before the first time it is used.

We corrected it for the first appearance in section 2.1.

<u>Additional changes:</u>

We changed a typo on page 16 l.27-18 (manuscript in discussion):

The average SZA during the low level flights over sea ice under cloudy conditions was 61° not 59°.

"These values hold for the ACLOUD observations with an average LWP during cloudy conditions over sea ice of 58 gm-2 and a SZA of 61°."

We corrected a wrong statement on p.16 l. 22-24 (manuscript in discussion):
"The non-linearity in the functional dependence of surface albedo and LWP spreads the frequency distribution, while the mode for cloud-free conditions is not affected. "

In section 4.1 we reduced the paragraph covering the ice fraction dependent scaling of the Gardner and Sharp (2010) parameterization, because only homogeneous sea ice distributions are discussed/showed with respect to the surface albedo-cloud interaction and the required introduction of the equation, which would distract from the section (p. 19 l.5-7):
"However, making use of the cosine weighted sea ice fraction I_f and its linear relation to the albedo, changes due to the surface albedo-cloud interaction can be scaled to the prevailing I_f by assuming diffuse radiative transfer (Lambertian albedo) (not shown in this study)."