Revision R03 Version 02, 27 November 2023

Manuscript Title: *Supercooled liquid water clouds observed over Dome C, Antarctica: temperature sensitivity and radiative forcing* **by Ricaud et al.**

RESPONSES TO THE EDITOR

Dear Dr. Ricaud,

I am in the possession of a review of your current manuscript. Overall, the reviewer was happy with the improvements you made to the manuscript, but has a few more things to look into. This should only be a minor revision before the manuscript can be published.

→ Dear editor, thank you very much for the confidence you had in our study despite the fact that it took some time for us to converge towards fully acceptable results. We have modified the article according to the review of the last reviewer. We have updated the date of the last access to all the databases to 27 November 2023.

We also modified the title to be consistent with the reviewer's comments regarding the term cloud radiative forcing (CRF) from

Supercooled liquid water clouds observed over Dome C, Antarctica: temperature sensitivity and radiative forcing

to

Supercooled liquid water clouds observed over Dome C, Antarctica: temperature sensitivity and ***cloud*** *radiative forcing*

Comments from Sarah Buchmann

Notification to the authors:
Checking your paper, I noticed that some of your tables contain coloured cells. Please note that this will not be possible in the final revised version of the paper due to HTML conversion of the paper. When revising the final version, you can use footnotes or italic/bold font. For now, the process will continue, but please note that the final version cannot be published by using coloured tables.

→ We have modified the incriminated Tables into:

Table 1. Cloud-free periods in December 2018-2021 detected from the LIDAR depolarization observations at Concordia. Time is in UTC. MM-NN means from MM (included) hour UTC to NN (excluded) hour UTC. “X” means no cloud-free period during that day. “ND” means no LIDAR data available. Bold cases mean that cloud-free irradiance calculations are impossible due to lack of some data (LIDAR, HAMSTRAD, BSRN or AWS).

Days	2018	2019	2020	2021
01	0-24	**9-18**	**ND**	**9-16**
02	0-21	**13-17**	**ND**	**7-8**
03	0-24	**6-16**	**ND**	**6-24**
04	X	**11-16**	**ND**	**0-24**
05	X	6-16	**3-16**	**12-19**
06	3-6	0-13	9-13	**2-12**
07	**1-16**	X	X	**0-24**
08	3-15	X	1-2	**0-10**
09	**2-16**	X	**4-14**	**10-17**
10	0-3	X	X	**ND**
11	X	4-17	0-1	**ND**
12	X	X	20-22	**ND**
13	11-13	10-14	0-12	X
14	22-24	17-18	X	5-12 & 17-20
15	4-8	**22-23**	X	3-6
16	**15-18**	X	**6-8**	11-24
17	18-19	**ND**	X	0-24
18	1-17	**ND**	16-17	0-3
19	0-24	**ND**	7-9 & 11-13	20-23
20	**0-12**	**ND**	20-22	16-19
21	X	**ND**	20-21	X
22	9-16	**ND**	ND	12-15
23	1-4	**ND**	**14-20**	X
24	X	**ND**	**11-14**	0-6
25	X	**ND**	9-15	**20-24**
26	12-18	**ND**	0-16 & 18-22	0-24
27	**10-11**	**ND**	0-2	0-4
28	**0-6**	**ND**	0-17	**10-14**
29	**X**	**ND**	0-18	**X**
30	**X**	**ND**	**7-24**	**X**
31	**10-12**	**ND**	0-18	**X**

Table 2. Gaussian functions fitted to the $N(x)$ function for $x = T$ (°C) or ΔF (W m^{-2}). Units of a_1, a_2, a_3, and c_0 are in count number for T and ΔF; units of μ_1, μ_2, μ_3, σ_1, σ_2, and σ_3 are in °C for T and in W m^{-2} for ΔF.

x	a_1	μ_1	σ_1	a_2	μ_2	σ_2	a_3	μ_3	σ_3	c_0
T	15.0 10^3	-31.5	1.45	5.0 10^3	-28.0	1.65	0.5 10^3	-19.0	2.5	-9.1 10^{-6}
ΔF_{net}	371.7	10.0	11.5	74.6	37.6	21.1	220.8	57.5	14.1	-10.2
ΔF_{LW}^{Down}	415.5	10.0	10.4	189.5	53.7	24.2	227.1	82.9	7.0	-18.5
ΔF_{LW}^{Up}	-	-	-	-	-	-	-	-	-	-
ΔF_{SW}^{Down}	190.5	-10.1	17.2	113.0	-80.0	54.6	-	-	-	-1.9
ΔF_{SW}^{Up}	282.4	-10.1	12.8	133.8	-75.0	41.8	-	-	-	8.3

Table 3. Coefficients of the relations $f(LWP) = \alpha + \beta \ln(LWP)$ for the temperature T or cloud radiative forcing components ΔF. Units of T and ΔF, as well as of their corresponding "α" values are in °C and W m^{-2}, respectively; units of β are in °C g^{-1} m^2 for T and in W g^{-1} for ΔF; units of LWP are in g m^{-2}. The last column shows the range of LWP values for which the relation is valid. $\alpha \pm \delta\alpha$ corresponds to the range of α values where the relationship is valid.

$f(LWP)$	$\alpha \pm \delta\alpha$	β	Valid range for T or ΔF	Valid range for LWP
T	-33.8 $\pm$ 1.5	6.5	$[-36; -16]$	$[1.0; 14.0]$
ΔF_{net}	-18.0 $\pm$ 10.0	70.0	$[0; 70]$	$[1.2; 3.5]$
ΔF_{LW}^{Down}	5.0 $\pm$ 15.0	65.0	$[0; 90]$	$[1.0; 3.5]$
ΔF_{LW}^{Up}	0 $\pm$ 5.0	0.0	$[-5; 5]$	$[0.0; 6.5]$
ΔF_{SW}^{Down}	30.0 $\pm$ 30.0	-130.0	$[-130; 0]$	$[1.5; 4.0]$
ΔF_{SW}^{Up}	30.0 $\pm$ 30.0	-110.0	$[-110; 00]$	$[1.5; 4.0]$

Anonymous Referee #3

Referee comment on "Supercooled liquid water clouds observed over Dome C, Antarctica: temperature sensitivity and surface radiation impact" by Ricaud et al.

In general, the authors revised their manuscript thoroughly, taking into account all reviewers' comments. The manuscript has been significantly improved.

I only have a few minor suggestions that could be considered before the final publication.

→ Thank you very much for your fruitful comments.

General Comments

The authors introduced the cloud radiative forcing. Starting with the definition of the net irradiance:

$$F_{Net} = \left(F_{LW}^{Down} - F_{LW}^{Up}\right) + \left(F_{SW}^{Down} - F_{SW}^{Up}\right) \quad (1)$$

the cloud radiative forcing ΔF_{Net} is difference between the net irradiances, in cloudy ($F_{Net,cld}$) and cloud-free ($F_{Net,cf}$) conditions (e.g., Stapf et al., 2020):

$$\Delta F_{Net} = F_{Net,cld} - F_{Net,cf} \quad (2)$$

The authors also refer to the difference between the individual components as cloud radiative forcing (CRF). As I understand it, radiative forcing only refers to the differences in net irradiance.

→ We understand this key point. We have modified the text accordingly throughout the manuscript. We now refer to CRF only considering the net irradiances, and how CRF is split into the individual components (F_{LW}^{Down}, F_{LW}^{Up}, F_{SW}^{Down} and F_{SW}^{Up}).

Below (Specific Comments) I have listed some examples of texts that should therefore be changed.

Specific Comments

Abstract:

L37/L38: Please use either "solar" or "shortwave" throughout the manuscript.

→ We now only use "shortwave" throughout the manuscript.

L40 and others: "net cloud radiative forcing" – remove "net", as the CRF is related to the net irradiance.

→ Yes see point above.

Introduction:

L66: "Bromwich et al. (2012) mention in their review paper that CCN and INPs are of various nature and large uncertainties exist relative to their origin and abundance over Antarctica." - Do you mean variability or uncertainties?

→ We are actually referring to "uncertainties" according to the first sentence of abstract in Bromwich et al. (2012): "*Compared to other regions, little is known about clouds in Antarctica.*"; and to the last sentence of this abstract "*While cloud monitoring over Antarctica from space has proved essential to the recent advances, the review concludes by emphasizing the need for additional in situ measurements.*"

L104: "the longwave downward" → "downward longwave", the same for the other quantities

→ Done throughout the manuscript.

L105: "At a given time, the impact of a cloud on the surface irradiance can be estimated by subtracting what would have been the cloud-free surface irradiance from the measured surface irradiance, to provide the so called "cloud radiative forcing"." – maybe you could write "At a given time, the impact of a cloud on the surface irradiance is estimated from the difference between the net irradiances, in cloudy ($F_{Net,cld}$) and cloud-free ($F_{Net,cf}$) conditions to provide the so-called ..." Why is the equation for the CRF not already given here?

→ We have modified the sentence and introduced the cloud radiative forcing there, including the relevant equation.

Section 3.1:

L201: "The same method is used for F. BSRN Fs are time interpolated to be coincident with the other parameters." I would delete the first sentence, since the irradiance is only interpolated in time and not in space (vertical direction like the temperature). "BSRN Fs" → "BSRN irradiances"

→ We have modified the text according to the reviewer's comments.

Section 3.2:

L223-L226: "The cloud radiative forcing (ΔF) can be defined as: …": see general comments

→ The issue of "cloud radiative forcing" has been carefully dealt throughout the manuscript.

L226: "Several studies have been performed …" – give references.

→ There is a misunderstanding in this sentence since we were referring to our own studies. We modified the sentence into:

We performed several studies (reference irradiances measured over days when clouds are absent, radiative transfer calculations) from which it resulted that the most robust method was to use a parameterization of the cloud-free downward longwave and shortwave surface irradiances widely used in the community.

L243-L246: Please note that the surface albedo of snow under cloudy conditions may differ from the surface albedo under cloud-less conditions (e.g., Gardner and Sharp, 2010, Stapf et al., 2020). Maybe mention it here since it is another source of uncertainty.

→ We have inserted the sentence proposed by the reviewer in the section "5.5. Sastrugi effect on the surface albedo" and included the two references.

L249: "Note that computationally simple, theoretically based parameterization for the broadband albedo of snow and ice can accurately reproduce the theoretical broadband albedo under a wide range of snow, ice, and atmospheric conditions (Gardner and Sharp, 2010)." – Why is this mentioned here? The albedo is not parameterized in this study.

→ We removed this sentence.

L256: "Screen-level temperatures are provided by the American automated weather station (AWS) situated at ~500 m from the Concordia base." – Can be removed. It was already mentioned before.

→ Removed.

Section 4.2:

L358-L359: "PDs of the cloud radiative forcing ΔF as a function of the LWP, for …" – CRF is ΔFnet, the others are only components that contribute to the CRF (see general comments)

→ Modified according to the reviewer's comments.

Section 5.1:

The section needs a little more interpretation. What is the critical temperature exactly? What does it tell us for this study?

→ We understand the point. Our (naïve) approach was simply to highlight that the exponential relationship between supercooled liquid water and in-cloud temperature we have observed in our study can be related to the theory that also shows this exponential behavior (see e.g. Figure 4 from Sippola and Taskinen (2018)) for temperatures less than 0°C.

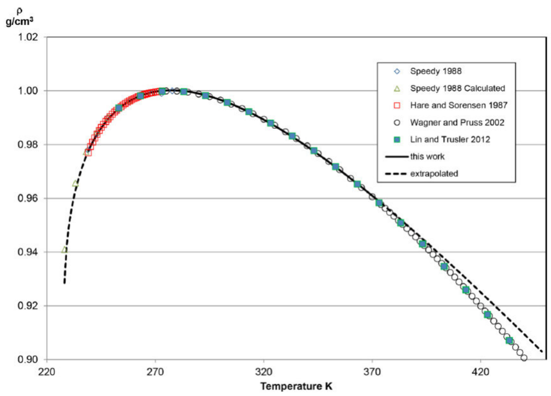

Figure 4. Assessed density ρ of liquid water compared with experimental data.[15,23,33,34] Dotted lines indicate extrapolated values. Data by Speedy[15] and Lind and Trusler[34] were not included in the assessment.

Figure taken from Sippola and Taskinen (2018).

In thermodynamics, a critical point (or critical state) is the end point of a phase equilibrium curve. In our study of supercooled liquid water dependence in temperature, the liquid–ice boundary terminates in an endpoint at some critical temperature Tc. Tc is about 224.8 K if water is pure and free of nucleation nuclei. But Sippola and Taskinen (2018) reviewed a value of Tc ~227-228 K (approx. -45°C) in the literature. Our study shows that, above Concordia, we could not observe SLWCs at temperatures less than -36°C that is consistent with the fact that the threshold temperature should be around -39°C (see the discussions on errors in section 5.3).

We have modified the text as follows (and changed the labelling of equation 18 into 17 since we removed one equation in this subsection).

Our study shows that, above Concordia, there is an exponential dependence of LWP on both temperature and cloud radiative forcing, that is to say supercooled liquid water exponentially increases with temperature in the range -36°C to -16°C. This is in agreement with the outputs from a simple model for thermodynamic properties of water from sub-zero temperatures up to +100°C (Sippola and Taskinen, 2018). The model shows that the density ρ (g cm^{-3}) of liquid water exponentially increases with temperature from -34°C to 0°C through the following relationship:

$$\rho = \rho_0 \exp\{-T_c(A + B\varepsilon_0 + 2C\varepsilon_0^{1/2})\} \tag{15}$$

where ρ_0 = 1.007853 g cm^{-3}, A = 3.9744 10^{-4} K^{-1}, B = 1.6785 10^{-3} K^{-1}, and C = -7.8165 10^{-4} K^{-1} are parameters; T_c is the critical temperature (K) and ε_0 (unitless) is defined as:

$$\varepsilon_0 = \frac{T}{T_c} - 1 \tag{16}$$

where T is temperature in K. In thermodynamics, a critical point is the end point of a phase equilibrium curve. In our study, the liquid–ice boundary terminates at some critical temperature T_c. T_c is about 224.8 K if water is pure and free of nucleation nuclei. Sippola and Taskinen (2018) reviewed a value of T_c ~227-228 K (approx. -45°C) in the literature. This is also in agreement with the results from our study showing that, above Concordia, we could not observed SLWCs at temperatures less than -36°C consistent with the fact that the threshold temperature to get SLWCs should be around -39°C (see the discussions on errors in section 5.3).

L406: "SR anomaly" – you mean the CRF here, I guess

→ Yes, it is a remnant of the very first version of the paper. We modified the term.

Section 5.5:

Figure 10 is not really needed.

→ We have removed this Figure and modified the Figure numbering accordingly.

L517-L518: "The large diurnal signal present in the observed surface albedo is likely the signature of the sastrugi effect." – It depends on sastrugi orientation (geometry) and sun geometry that affects the surface albedo. Even with a flat snow surface, one would expect the surface albedo to depend on the SZA (Gardner and Sharp, 2010). You might mention that.

→ We modified the sentence into:

“The large diurnal signal present in the observed surface albedo is likely the signature of 1) the sastrugi orientation and also 2) the sun zenith angle which impacts on the surface albedo even with a flat snow surface (Gardner and Sharp, 2010).”

L525: “We can state that the sastrugi effect on the observed cloud-free surface albedo at Concordia is successfully fitted by two sine functions of 24h and 12h periods …” – Since the orientation of sastrugis could be different, would it be possible that your fit is more related to the SZA effect?

→ This is a good comment. We cannot rule out that the SZA effect also impacts on the surface albedo. Sastrugis orientation depends on the wind orientation that is climatologically blowing to the North at Concordia. Therefore, it is difficult to quantify the impact of these two effects (sastrugis and SZA) on the diurnal cycle of the surface albedo. We have inserted a new sentence:

“We cannot rule out that the diurnal cycle of the surface albedo is also impacted by the diurnal cycle of the solar zenith angle.”

Section 5.6:

L545: Eq. (18) assumes a linear dependence between cloud fraction and CRF. Perhaps it should be mentioned that there are 3D radiation effects in nature that contradict this assumption.

→ We have inserted a new sentence, updating “Equation (18)” into “Equation (17)”.

“Equation (17) assumes a linear dependence between cloud fraction and cloud radiative forcing although, in nature, there could be three-dimensional radiation effects.”

Technical comments

L285: “increases to values of +40-90 W m-2” – Here and elsewhere better write “+40 to 90 W m-2”

→ Done throughout the manuscript.

L551: “… over Antarctica of about 12, 10 and 7 W m-2, respectively.” → 12 W m-2, 10 W m-2, and 7 W m-2

→ Done

References:

Gardner, A.S. and Sharp, M.J.: A review of snow and ice albedo and the development of a new physically based broadband albedo parameterization. Journal of Geophysical Research: Earth Surface, 115(F1), 2010.

→ This reference was already present in the previous version of the manuscript.

Stapf, J., Ehrlich, A., Jäkel, E., Lüpkes, C., and Wendisch, M.: Reassessment of shortwave surface cloud radiative forcing in the Arctic: consideration of surface-albedo–cloud

interactions, Atmos. Chem. Phys., 20, 9895–9914, https://doi.org/10.5194/acp-20-9895-2020, 2020.

→ Reference inserted in the revised manuscript.