Relevant changes made to the manuscript after the review phase

1. The title and abstract have been changed to better represent the content of the manuscript
2. The introduction has undergone major revision to increase its clarity
3. The description of cloud properties and fluxes data has been rewritten in more detail
4. New results were presented with respect to the optical thickness of clouds and their water content in the two thermodynamic phases
5. The "Discussions and Conclusions" section has been split. Now the manuscript consists of a "Discussions" and "Summary and conclusions" section.

Answer to Anonymous Referee #1, 23 Feb 2022

`https://doi.org/10.5194/acp-2022-28-RC1`

Structure of the document:

1. The remarks by the referee are black and labelled as R$_{1...n}$
2. Our answers are red and labelled as A$_{1...n}$. For each answer, we explicitly say how the text will be updated together with new figures, where appropriate.
3. Relevant non-trivial changes are verbatim reported in blue and labelled C$_{1...n}$ with the line numbers of the revised manuscript.

Before delving into the specific comments of the referee, we want to thank him for taking the time to read out work.

R1

This paper uses extensive analysis of changes in the radiation balance over the Arctic to consider the causes and effects of different trends.

A1

We consider that the referee has summarised some key elements of what is reported in this paper.

As a matter of fact, we focused initially on creating a long term record of the reflectance at the top of the atmosphere in the solar spectral regions. We then analysed the trends at pan-Arctic and regional scale. In spite of the melting of ice, we find in spring (April May and June) and in summer (July August and September) trends across the Arctic, which are smaller than that we expect for the reduction of the surface albedo averaged over the Arctic. This led us to investigate the origin of this behaviour. We investigated the behaviour of available cloud data products in the Arctic and their trends. Our explanation is that the loss of surface albedo and reflectance at the top of the atmosphere is compensated by an increase in cloud reflectance. We then went on to investigate the possible reason for this increasing cloud reflectance and we attribute it to a reduction in cloud ice optical thickness and an increase in cloud water optical thickness.

R2

It is a highly timely and very important study that should be published. It shows how satellite can be used to effectively address a question that has been very much deliberated in the scientific press; Do changes in clouds, either macrophysical or microphysical, due to climate change affect the radiation balance over the Arctic, especially when considering the accelerated ice melt and snow drawback and suggested changes in cloud microphysics and the potential importance in aerosols. It is very welcome and I do encourage the authors to revise and resubmit this paper.

A2
We thank the referee for his effort in reading our paper. We shall answer the issues the referee has raised.

R3
However, it is abundantly clear that the study is not finished yet; in fact, it is so poorly put together and presented that this is the reason I feel I have to recommend that the paper is rejected at this stage. Paired with poor writing this just simply goes beyond the scope of a major revision.

A3
We regret that the referee does not consider the manuscript worthy of publication. However, we would like to point out that prior to submission to ACP, the manuscript and its results have been confidentially brought to the attention of several (native English speaking) colleagues. They are active in Arctic research, both modeling and observation-based, algorithm development, and data generation. The encouraging feedback we received and the improvements that resulted from the discussions convinced us that our work was ripe for scientific scrutiny.

R4
The introduction has no real thread and just repeats various statements as if they were of the same significance and the text doesn't lead up to the motivation and background for this study.

A4
We consider that the introduction follows a clear logic and the corresponding narrative is briefly presented schematically below:

lines 11–17	Arctic climate change and Arctic Amplification are briefly introduced within the context of global climate change.
lines 18–26	The role of clouds is introduced and our work is justified as complementary to in situ measurement endeavours.
lines 27–34	A brief description of the Arctic environment is given. The spectral reflectance measurements at the top of the atmosphere are introduced.
lines 35–76	We introduce the first cloud property, relevant to Arctic climate change: cloud fractional cover (CFC). We review the main literature and extract the scientific findings that describe its influence on Arctic climate. We note that the role of CFC in Arctic warming is controversially debated.
lines 77–85	We discuss the optical and micro-physical properties of clouds (thickness, liquid water path and effective radius), which are important factors in modulating the SW and LW radiation budget across the Arctic.
lines 86–95	We propose the investigation of spectral reflectance and cloud product trends to resolve disagreements found in the literature.
lines 96–100	The structure and the aim of the paper are outlined.

We insert a new paragraph before lines 96–100 in which we explain that the use of spectral reflectance supports the assessment of the relative roles of CFC and optical and micro-physical cloud properties in modulating the radiation balance.

Note, however, that the introduction has undergone major revisions and the narrative includes clearer transitions between the topics listed above.

C4

(Lines 112-116) From the above review of our current knowledge of the changing conditions in the Arctic, we conclude that investigations of the RTOA and the cloud properties over the past two decades provide valuable insight into the evolution of the Arctic climate. To achieve this goal, we have prepared a consolidated RTOA data set from 1995 to 2018 (https://doi.pangaea.de/10. 115 1594/PANGAEA.933905). This data set from satellite sensors comprises backscattered radiation at TOA in the SW solar spectral range.

R5

The text quotes huge amounts of numbers but doesn't lead the reader to the important ones and it is much to long for the message (65 figure panels in the manuscript alone and another 44 in the appendices). The authors are piling definitions and numbers upon numbers and completely forget the narrative;

A5

While only three numbers are given in the introduction (at lines 35 - 40), we report the climatological values of cloud fractional cover in the literature. In the rest of the paper numbers are provided because evidence-based research rests upon quantitative assessments.
Regarding the number of panels and figures, we note that our analysis must be regional and seasonal, given the pronounced variability in the Arctic environment.

R6

The paper is basically unreadable and I wouldn't have read it if had not had the task of reviewing it - in fact, I gave up when I got to the discussion and conclusion section - which is almost a third of the paper. I'm just saying!

A6

The "Discussion and Conclusions" section takes up a third of the text because the topic of Arctic climate change is complex, the body of literature is extensive and our approach is comprehensive in analysing the data.

For the sake of readability, we split the section "Discussion and conclusions". We will then discuss the results in the first part and list our conclusions in the latter.

R7

A few examples: The statement that the sea ice will be gone by 2035 (line 11) is not representative of current understanding; yes, at the current rate it will eventually be gone but the recent IPCC report concludes that some ice will remain if we can keep the global warming below 2 degrees.

A7

As a matter of fact, the IPCC report AR6 - Working Group I - Chapter 9 verbatim reports:

> "The Arctic Ocean will likely become practically sea ice free during the seasonal sea ice minimum for the first time before 2050 in all considered SSP scenarios. There is no tipping point for this loss of Arctic summer sea ice (high confidence)."

Consequently we consider the cited work by Guarino et al. (2020), in which it is stated that the sea ice will have effectively vanished by 2035, a better representation of our current understanding.

This is not only because that paper is one of the most recent studies focusing on this topic, but also and foremost because in all CMIP6 scenarios, for almost all models, the Arctic is projected to be sea ice free well before 2050 (Notz D. & SIMIP Community, 2020).

Notz D. & SIMIP Community (2020) is the main reference in the IPCC report.

One of the co-authors of our work (Narges Khosravi) has co-authored that paper. We quote its conclusions:

> "**However, the clear majority of all models, and of those models that best capture the observed evolution, project that the Arctic will become practically sea ice free in September before the year 2050 ...** "

Figure 3-c of the aforementioned paper shows that even for a scenario with temperatures below the 2 degrees (light blue dots, first column from the left), the majority of the model outputs predict the vanishing of Arctic sea ice by years 2035–2038.

The Arctic, with a remaining sea ice surface area <1 million km^2, is termed "sea ice free" in the cited references and it is not our wording.

`https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_09.pdf`

Guarino, MV., Sime, L.C., Schröeder, D. et al. Sea-ice-free Arctic during the Last Interglacial supports fast future loss. Nature Climate Change. 10, 928–932 (2020). `https://doi.org/10.1038/s41558-020-0865-2`

Notz, D., & SIMIP Community (2020). Arctic sea ice in CMIP6. Geophysical Research Letters, 47, e2019GL086749. `https://doi.org/10.1029/2019GL086749`

The Notz D. & SIMIP Community (2020) reference will be added to the introduction with an appropriate sentence.

C7

(Lines 21–26) The Arctic near-surface increase of temperatures is about twice that of the global average during the past four decades (Soedergren and McDonald, 2022). This phenomenon is referred to as "Arctic Amplification" (Serreze and Francis, 2006). As a consequence, the most recent climate projections indicate that the Arctic may be free of sea ice by the summer of 2035 (Guarino et al., 2020). Even if global temperatures are held to the target of a 2 C increase, the Arctic sea ice is projected to disappear (i.e. sea ice extent < 1 million km^2) in September between 2035 and 2038 by the majority of the models in the Climate Model Intercomparison Project Phase 6 (CMIP6, Notz and Community (2020)).

R8

The Arctic warming (line 12) is, however, probably larger than twice the global average. Arrhenius (line 14) may be of historical importance but his method was likely incorrect and he was "lucky"

A8

Regarding the Arctic warming larger than twice the global average, we report here Fig. 1 in Ballinger et al. (2021). The reference belongs to the regularly updated Arctic Report Card series within the Arctic Program managed by NOAA. We consider this source reliable.

From Figure 1 it can be seen that the ratio between the global average and the Arctic average of Surface Air Temperature (SAT) is approximately 2 (please, note how the Arctic region is defined north of the 60th parallel. See later comment by the referee.)

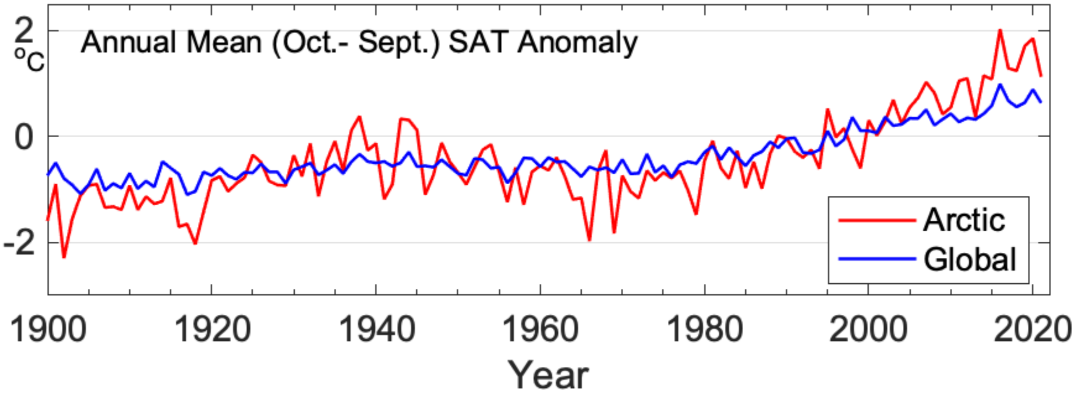


Fig. 1: Mean annual SAT anomalies (in °C) for weather stations located on Arctic lands, **60–90° N (red line)**, and globally (blue line) for the 1900–2021 period (n=122 years). Each temperature time series is shown with respect to their 1981–2010 mean. Source: CRUTEM5 SAT data are obtained from the Climate Research Unit (University of East Anglia) and Met Office.

In addition, CMIP6 model mean shows that the median of multiplicative factor of Arctic warming with respect to the global average is roughly 2.2, excluding the 5th and 95th percentiles. See Fig. 2 from Södergren and McDonald (2022).

Södergren, A. H., and McDonald, A. J. (2022). Quantifying the role of atmospheric and surface albedo on polar amplification using satellite observations and CMIP6 Model output. Journal of Geophysical Research: Atmospheres, 127, e2021JD035058. `https://doi.org/10.1029/2021JD035058`

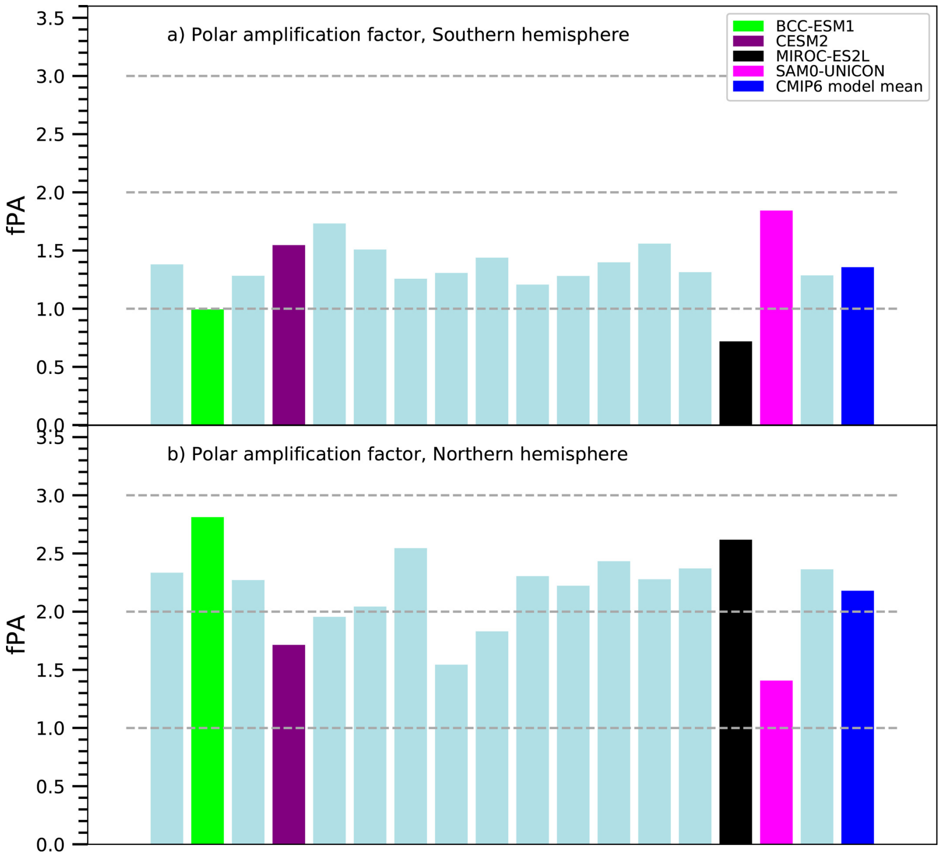


Fig. 2: Polar amplification factor from CMIP6 models (from Södergren and McDonald, 2022).

With regard to *the luck of Arrhenius*, we invite the referee to read the paper by Rohde et al. (1997). They highlight the merit and legacy of his work. Arrhenius not only thought of a realistic Sun-atmosphere-Earth model, but also considered the two "selective absorbers" known at the time: water vapor and carbonic acid. The latter be used by Arrhenius synonymously for carbon dioxide.

The pioneering role of Arrhenius is also acknowledged in two aspects.
First, he was able to bridge conceptually his paleo-glaciology studies with future scenarios of man-made greenhouse gas emissions. This was remarkable and well ahead of his time (i.e. Keeling initiated carbon dioxide monitoring only in 1957), given the lack of reliable atmospheric measurements of greenhouse gases.
Second, he advocated atmospheric chemistry as a fundamental pillar of Earth Sciences. Arrhenius approach paved the way for an interdisciplinary Earth Science, which is one of the cornerstone of the IPCC reports, as Rohde et al. clearly explain.

Ballinger, T. J., Overland, J. E., Wang, M., Bhatt, U. S., Hanna, E., Hanssen-Bauer, I., Drukenmiller, M. L. (2021). Surface air temperature. Arctic Report Card.

`https://doi.org/10.25923/53xd-9k68`

Rohde, H., Charlson, R., & Crawford, E. (1997). Svante Arrhenius and the greenhouse effect. Ambio, 2-5.

C8
(Lines 13–20) The size of a temperature increase from a doubling of the column of carbon dioxide, CO2, in the atmosphere was first quantified by Svante Arrhenius in 1896 (Arrhenius, 1896). This was a remarkable achievement and ahead of his time given the lack of reliable atmospheric measurements of greenhouse gases (for more details see Rodhe et al., 1997, and references therein). The first routine monitoring of CO2 fraction in dry air was initiated by Charles Keeling at the Mauna Loa Observatory only in 1957 (Keeling, 1958, 1960; Keeling et al., 1976). This led eventually to the recognition of the impact of the anthropogenic release of greenhouse gases on the global surface temperature, which has become an increasingly important topic of scientific interest, public debate and concern and international environmental policy, since at least 1990. However, the Arctic is a special case (Serreze and Barry, 2011).

. . .

(Lines 21–22) The Arctic near-surface increase of temperatures is about twice that of the global average during the past four decades (Soedergren and McDonald, 2022).

R9
While the concern of scientists and public about the fate of the Arctic (lines 15-17) is much more recent than the 1990's. This was when the first IPCC report was published and if you download that and have a look, you will find that to the extent the Arctic is mentioned it is mostly either in the context of how little we know or how badly the models deal with the Arctic.

A9
The subject of the sentence is not the fate of the Arctic but the release of anthropogenic gases and its impact on surface temperatures. We quote again lines 15-17:

> "The impact of the anthropogenic release of greenhouse gases on the surface temperature has become an increasingly important topic of scientific interest, pubic debate and concern and international environmental policy, since at least 1990."

As a side note, one of the oldest headlines in the mainstream press raising the issue of a melting Arctic dates December 3, 1922. It appeared in the American Weekly magazine of the Washington Times. We invite the referee to read the column "Strange Things Happening in the Frozen Arctic". It can be found at the end of this document, labeled Fig. 3.

Source: https://www.rfcafe.com/miscellany/smorgasbord/images/Arctic-Icebergs-Melting-Washington-Times-December-3-1922-rf-cafe.jpg

R10
All these superlatives seem to be used to underscore the importance of the study, but on me they act as a turn-off; if you need to exaggerate this way, the result cannot be very important. But it is and the

framing of important facts is also important!

A10

The framing has been made clearer. We have rewritten the introduction (Lines 13–126) and the justification of the used data sets (Lines 185–273). New results for total optical thickness and condensed water in clouds for the liquid, ice and total phases have been generated, therefore improving their description and interpretation for a changing Arctic surface. Finally, we split the last section into discussion and conclusions. Specifically, we have framed our findings relating them to independent measurement throughout, outlining future research needs (Lines 541–564), and to modelling results (Lines 565–592).

R11

Moving on, the reason that the clouds are considered a major reason for much of uncertainty in climate projections (line 18) is not that they affect the radiation (line 19-20); off course they are! It because models describe clouds so poorly, because it is so very difficult to model.

A11

We update the sentence accordingly as follows.

C11

(Lines 27–30) Clouds play an important role in determining the climate of the Arctic. Modeling the changing behavior of clouds sufficiently accurately is identified as the most uncertain factor in the climate projections of greenhouse gas forcing (Zelinka et al., 2020). This is particularly the case in the Arctic, where the modulation of radiation by clouds in the shortwave (SW) and longwave (LW) spectral regions is not adequately simulated by state-of-the-art models.

R12

Satellite observations are an important part of this but the work cited on line 24 does not "rely on" (line 25) on satellite observations.

A12

Our use of the English language seems appropriate (e.g. `https://www.merriam-webster.com/dictionary/relyon/upon`) and we consider that in situ measurement campaigns, like those described in Wendisch et al. (2019) and Shupe et al. (2021), rely on satellite observations to tackle the understanding of Arctic climate change. For the sake of clarity, we rewrite the sentence as follows.

C12

(Lines 34–36) To address these objectives, ambitious measurement endeavours (Wendisch et al., 2019; Shupe et al., 2021) have exploited the synergistic use of measurements by on-ground, ship and airborne sensors. However, another complementary source of knowledge are measurements by satellite sensors that provide synoptic coverage of the Arctic clouds over long time scales.

R13

It is well known that different retrievals based on AVHRR are very different (line 42-44); yet it is used again here without illustrating why we should now all of a sudden believe in this retrieval.

A13

In addition to this response, please see also A15, A19, A47 in the answer to the second referee.

The retrieval of cloud data products is comprehensively introduced citing the relevant literature. Section 2.2 of the paper describes the AVHRR data set used in this work. In that section we summarize the key points of the data set and how it has been improved. We correctly cite the references needed to understand and judge the generation, the validation and the quality assessment of the AVHRR cloud data set. We provide actual assessments of the biases of the broadband fluxes with respect to independent sources. We discuss our technical approach for its usage in Appendix B and C.

To facilitate the work of the referee, we list below the key points :

1. This AVHRR dataset is in its 3rd reprocessing and the algorithm used to generate it has 15 years of development starting with ATSR-2 onboard ERS-2.

2. Improvements and validation have been documented throughout the publications cited by us and are traceable.
   `https://climate.esa.int/en/projects/cloud/key-documents/`

3. Specifically, the Annex A of the following document lists the independent sensors the dataset used for validation.
   `https://climate.esa.int/media/documents/Cloud_Product-Validation-and-Intercompariso`
   `v6.0.pdf`

4. AVHRR spectral channels have been spectrally and radiometrically calibrated by comparison with SCIAMACHY observations. SCIAMACHY is well known for its calibration. The first author personally helped DWD in this activity
   (see `https://essd.copernicus.org/articles/12/41/2020/#section11`).

   This calibration improves the value of our study, because the part of the study dealing with TOA reflectance uses radiometrically consistent with those retrieved from SCIAMACHY. Thus, the trends in reflectance can be readily related to those in cloud properties derived from AVHRR.

5. The algorithm deriving cloud properties uses optimal estimation: full uncertainties are provided. They are accounted for calculating the correlation length of cloud properties as function of the subsampling of the cloud fields. See Section 2.4.1, Eqs. 1–5, in `https://essd.copernicus.org/articles/9/881/2017/essd-9-881-2017.pdf`

6. AVHRR cloud mask utilises an ANN (Artificial Neural Network) - trained on CALIOP surface mask, which is the gold standard in Arctic atmospheric research.

7. In-cloud profiles are corrected with CALIOP profiles to account for photon penetration depth, so that the retrieved cloud altitude is not the radiative height of a cloud, but the scattering height. The latter is closer to the physical top of the cloud.

8. AVHRR fluxes are computed using the cloud properties of the algorithm itself and are not from other sources. This eliminates co-registration issues and it enables direct relationships between cloud properties and fluxes to be determined.

9. The AVHRR record is constructed from different sensors with different overpass times and different calibration issues. This is accounted for in the trend model, in which we instruct the objective function to infer anomalies for each sensor at a time (see Appendix C of our paper).

10. The trend model accounts for the non-gaussian part of the record evaluating the effective portion of randomness, after D. S. Wilks. Resampling Hypothesis Tests for Autocorrelated Fields. Journal of Climate, 10(1):65–82, 01 1997.

We consider that bullet 4 about cross-calibration between AVHRR and SCIAMACHY channels is of importance to measure and we plan add this to Section 2.2 accordingly, together with relevant information from the response to the second referee.

C13

(Lines 185–204) In our study, the RTOA data is complemented by a record of cloud properties and broadband fluxes at TOA and BOA. These are inferred from the afternoon orbit (PM) of AVHRR sensors onboard the POES missions. In spite of the availability of the morning orbit (AM) AVHRR series, we found that only the AVHRR PM series fulfilled the calibration stability requirements which allows trends' assessment to be made. Inspection of the time series of cloud properties and fluxes for the AM series showed that the drifts of the NOAA-12 platform before 2003, changing local overpass times, lead to calibration offsets and that the scan motor errors of the NOAA-15 platform to data gaps (Cloud_CCI Working Group, 2020). One good reason for choosing this AVHRR record is the number of studies using these data in the Arctic. Our choice is driven by the maturity of the AVHRR data set of measurements, its popularity, and by its successful use by the advanced, most recent, retrieval algorithm exploiting it. This AVHRR data set is in its 3rd reprocessing and the algorithm used to generate it has 15 years of development starting with ATSR-2 onboard ERS-2. While improvements and validation have been documented in traceable documents (https://climate.esa.int/en/projects/cloud/key-documents/), the cloud and flux records are presented by Stengel et al. (2020, and references therein). Some features, that distinguish this data record from older AVHRR records, are as follows: i) the channels in the solar spectral range have been cross-calibrated with SCIAMACHY channels. SCIAMACHY is recognised for its accurate radiometric and spectral calibration. Because the part of our study dealing with RTOA is conceived in a way that the record is radiometrically coherent with SCIAMACHY (see App. A), this intra-band correction relates reflectance changes at visible wavelengths detected by SCIAMACHY to those by AVHRR, ingested in the cloud retrieval algorithm, which calculates τ and cloud albedo; ii) the cloud mask uses a neural network, trained on CALIOP data to take into account the extent of the underlying bright Arctic surface; iii) CTH has been calibrated using CALIOP profiles to account for the penetration depth of radiation inside a cloud. This is needed because the retrievals of CTH from all infrared thermal channels are influenced by this effect and yield a radiative cloud top height, lower than the physical cloud top.

R14

The ice-mass loss for Greenland is attributed to a reduction in cloud fraction in summer (line 53-54) without a proper reference; I tend to believe that global warming has some influence as well.

A14

The logical reasoning is to be followed in its entirety until the end of the paragraph. The reference exists and reads Hofer et al. (2017) at line 55.

We will clarify this issue by stating that a decrease in cloudiness is not an independent process per se, but is also affected by large-scale synoptic meteorological processes.

Hofer, S., Tedstone, A. J., Fettweis, X., and Bamber, J. L.: Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet, Science Advances, 3, `https://doi.org/10.1126/sciadv.1700584`, 2017.

C14

(Lines 67–72) Hence, a decrease in summer CFC over Greenland is held responsible for the acceleration of the loss of ice mass and, consequently, a decrease of the albedo and spectral reflectance at TOA (RTOA). A decrease in cloudiness implies an increase of SW downwelling fluxes at the surface. This pattern is correlated with the North Atlantic Oscillation (Hofer et al., 2017) and anticyclonic activity promoting adiabatic tropospheric warming of subsiding air masses (Shahi et al., 2020). These results indicate that Arctic cloudiness is not only dependent on the underlying surface, but is also affected by synoptic scale meteorological processes.

R15

Ocean areas are quoted frequently without accounting if they are ice covered or not (first on line 59) which is a very important distinction; not all of the Arctic Ocean is always ice covered which is an important part of this study. Moreover, the Arctic seems to be defined as being everything between 60 and 85 degrees north. Not only does that miss a fair portion of the central Arctic; it also includes most of the Northern North Atlantic including Iceland and the Faroe Islands, large parts of which is never affected by sea ice, half of Sweden and Norway and almost all of Finland; much of this would not be considered Arctic at all.

A15

Please, see also A25 in the response to the second referee.

In Section 2.1 we discuss the reason for the latitudinal threshold at 85N.
Figure 2-c clearly demonstrates that the three sensors used for reflectance have different terminators. The 85N parallel is the northernmost meaningful threshold for common sampling. We have already reported the time series of Arctic temperatures in Fig. 1 in this document, which are averaged in the latitudinal belt 60–90N. We consider the source of Fig. 1 reliable.
In literature the south parallel defining the Arctic can be also placed at 65N. However, this latitude would still include parts of the land masses adjoining the more central Arctic zones. Nevertheless, they are of interest because the central Arctic exchanges energy, momentum, and fluxes with adjacent low-latitude regions. Well aware of this geographic conformation, we opted also for a regional analysis, subsetting the Arctic into twelve climatic zones to highlight shared, or distinct, patterns of behavior.

C15

(Regarding ice-covered areas, Lines 308–312)
To answer these questions in the following, we map RTOA in the Arctic, gridded at 1 × 1.5 degree latitude and longitude. Fig. 5 shows the spatially resolved RTOA trends for 510, 560, 620 nm over the Arctic region for AMJ and JAS. The mean seasonal sea ice extent is superimposed and colored green for year 1996 and purple for 2017. Sea ice extent is identified as those surfaces with at least local 75%

sea ice concentration. Data of sea ice concentration are from Walsh et al. (2019).

. . .

(Regarding the northernmost latitude at 85 N, Section 2.1, Lines 157–167)
While the measurement of solar radiation scattered back to the TOA by GOME, SCIAMACHY or GOME-2 takes place only during daylight, radiation in the thermal infrared ($\lambda > 4$ μm), required to record the thermal emission from the surface and the atmosphere, is not measured by these sensors. Because of the different sensors' swath widths, the RTOA measurements in the solar spectral range have a northern latitude boundary (or terminator). This boundary is illustrated by plotting the pan-Arctic annual cycle of RTOA in Fig. 2. At the three wavelengths 510, 560, and 760 nm, the seasonality shows that summer months have lower RTOA and higher otherwise. This darkening of the Arctic can also be seen by comparing the years at the beginning of the record, 1996, with the most recent ones. However, this behaviour occurs only between April and September. These are the months when the individual terminator of the three sensors reaches the latitude 85 N, this being the spatial threshold of common spatial coverage we set in the monthly average. As shown in Fig. 2, the other months (October to March inclusive) show that recent years are brighter (higher RTOA) than those at the beginning of the time series. This is because the individual terminators move further south (Fig. 2-c) and the coverage is considered insufficient for this to be studied further.

R16

While it is true that Pithan et al. (2014) identifies the vertical structure of the atmosphere (the lapse-rate effect) as the primary factor for Arctic amplification the difference to the next important process - the albedo feedback - is not large and the whole argument rests on models; not observations. By the way, saying that "temperature-related processes dominate the Arctic warming" is just plain thoughtless; what else is warming but a change in temperature?

A16

We agree that the sentence seems obscure. We have not written "temperature dominates the Arctic warming" but we have written "Temperature-related processes dominate the Arctic warming". Please see A8 in the response to the second referee.

C16

(Lines 87–97) For example, with the increase of Arctic temperatures, the thermodynamic equilibrium between water vapor, liquid water and ice is altered, which imbalances the phase of clouds in presence of aerosol particles (cloud condensation nuclei - CCN - or ice nucleating particles - INP). Dependent on the cloud phase, the particle radius changes: 90 liquid droplets being typically smaller than ice crystals (Mioche et al., 2017). This in turn affects the average optical thickness of clouds. The liquid and ice phases in the clouds interact differently with radiation in the solar and in the terrestrial spectral range. Already early studies (Curry et al., 1996) stressed that the additional presence of an underlying cold, bright surface and frequent temperature inversions impact atmospheric radiation budget through processes involving water condensate in form of liquid and ice clouds as a function of temperature profile. In a warming Arctic, it is expected that clouds will increase their liquid water content and thus reflect more SW radiation (Boisvert and Stroeve, 2015; Ceppi et al., 2016; Cesana and Storelvmo, 2017).

Curry, J.A., Schramm, J.L., Rossow, W.B. and Randall, D. Overview of Arctic cloud and radiation characteristics. Journal of Climate, 9(8), pp.1731–1764, 1996

Cesana, G., and Storelvmo, T. (2017), Improving climate projections by understanding how cloud phase affects radiation, J. Geophys. Res. Atmos., 122, 4594–4599, `doi:10.1002/2017JD026927`.

Boisvert, L.N. and Stroeve, J.C.. The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. Geophysical Research Letters, 42(11), pp.4439–4446, 2015.

R17
On Line 96 we are told there are three reasons for this paper only to be given four reasons.

A17
We will replace "three" with "four".

R18
The whole introduction is just confusing, sometimes borderline wrong, and doesn't lead the reader to the conclusion that this study is important at all.

A18
We consider that we have demonstrated that the introduction is well structured (see A4), that it cites the full body of literature relevant to the purpose of our study, that it is scientifically accurate and precise in extracting and presenting the correct information.

Following the suggestions of both referees, we made a major revision of the full introduction.

R19
On Line 131 is an unexplained "common north parallel" and on the following line there is an unexplained "darkening of the Arctic". On line 142-143 there is a transition in June while the figures show a transition through the entire spring. This is followed by "transitions increasingly approaching the summer solstice" which I don't understand and an argument that the day with the largest solar radiation needs to be the seasonal demarcation; why then is spring followed by summer and not autumn? I can buy the seasonal division based on what I see in the figures; that makes sense to me. So please don't add unjustified arguments that only muddies the water.

A19
The "*common north parallel*" is clearly explained as the northernmost latitude that is sensed by all three sensors GOME, SCIAMACHY and GOME-2. Their swath widths differ, so does their latitudinal sampling. Figure 2-c demonstrates this effect (see lines 129–138).

The "**darkening of the Arctic**" is also clearly explained at **lines 129–138**, by looking at the colors of the annual cycle of spectral reflectance for all three panels of Figure 2: brighter colors (1996) have greater values than the darker ones (2018), meaning a brighter Arctic at the beginning of the time series and a darker Arctic at the end of the time series. The yearly cycle of spectral reflectances shows a darkening of the Arctic as function of time, but only between April and September.

To explain the *transitions of reflectances between months* and the *demarcation of the seasons* we need a more articulated reasoning. This refers to **lines 139–145** of the manuscript.

We recall that the definition of seasons is arbitrary and is determined by the breakpoints of the variable under consideration. In general, seasons can be astronomical, meteorological or climatological. Provided that our study deals with 20 years of data, meteorological seasons are not useful and we will not discuss them hereinafter. The astronomical seasons for the Northern Hemisphere are April May June (AMJ) for spring and June August September (JAS) for summer. See Figure 1 in Cannon (2005). Climatological seasons are defined ad-hoc. One example is the Indian monsoon season. It stretches beyond the traditional breakpoints. There was the need to redefine the monsoon seasons looking at a more meaningful variable (i.e. vertically integrated moisture transport) than rainfall rates. See Fasullo & Webster (2003).

A more subtle but fundamental motivation of ad-hoc season definition is to calculate trends that are attributable to specific and different processes, which in turn determine the breakpoints in the time series of the variable under study (in our case, the spectral reflectance).

Also said: **a trend by a certain process 1 in AMJ should not be mixed with a trend by process 2 in JAS**. The question is if we have a clear breakpoint in the time series.

Figure 2 of our manuscript shows the annual cycle of measured TOA reflectance. It is evident from the measurements that the Arctic reflectance has a breakpoint between June and July. From April to June the reflectivity of the Arctic is dynamically decreasing (high-to-low). From July to September is flat.

Do the measurements point to different processes causing the steep decrease of pan-Arctic reflectivity in AMJ and flat reflectivity in JAS? Yes, they do. Recent studies show that Arctic albedo flattens by April and May due to snow cover changes and by June due to sea ice changes (Smith et al., 2020) and the timing of this breakpoint over Arctic waters is increasingly approaching summer solstice (Letterly et al. 2018).
Therefore, we do not define Arctic spring as the customary MAM (March April May) but as AMJ instead. Likewise, we do not define Arctic summer as the customary JJA (June July August) but as JAS instead.

Cannon, A. J. (2005), Defining climatological seasons using radially constrained clustering, Geophys. Res. Lett., 32, L14706, `https://doi.org/10.1029/2005GL023410`.

Fasullo, J., & Webster, P. J. (2003). A Hydrological Definition of Indian Monsoon Onset and Withdrawal, Journal of Climate, 16(19), 3200-3211. `https://doi.org/10.1175/1520-0442(2003)016%3C3200a:AHDOIM%3E2.0.CO;2`

A. Smith, A. Jahn, and M. Wang. Seasonal transition dates can reveal biases in Arctic sea ice simulations. The Cryosphere, 14(9):2977–2997, 2020. doi:10.5194/tc-14-2977-2020. `https://tc.copernicus.org/articles/14/2977/2020/`.

A. Letterly, J. Key, and Y. Liu. Arctic climate: changes in sea ice extent outweigh changes in snow cover. The Cryosphere, 12(10):3373–3382, 2018. doi:10.5194/tc-12-3373-2018. `https://tc.copernicus.org/articles/12/3373/2018/`.

We will update the section adding a paragraph with more background about the seasonal demarcation and the implication of adopting a different temporal subsetting.

C19

(Lines 157–167) While the measurement of solar radiation scattered back to the TOA by GOME, SCIAMACHY or GOME-2 takes place only during daylight, radiation in the thermal infrared ($\lambda \geqslant 4$ μm), required to record the thermal emission from the surface and the atmosphere, is not measured by these sensors. Because of the different sensors' swath widths, the RTOA measurements in the solar spectral range have a northern latitude boundary (or terminator). This boundary is illustrated by plotting the pan-Arctic annual cycle of RTOA in Fig. 2. At the three wavelengths 510, 560, and 760 nm, the seasonality shows that summer months have lower RTOA and higher otherwise. This darkening of the Arctic can also be seen by comparing the years at the beginning of the record, 1996, with the most recent ones. However, this behaviour occurs only between April and September. These are the months when the individual terminator of the th ree sensors reaches the latitude 85 N, this being the spatial threshold of common spatial coverage we set in the monthly average. As shown in Fig. 2, the other months (October to March inclusive) show that recent years are brighter (higher RTOA) than those at the beginning of the time series. This is because the individual terminators move further south (Fig. 2-c) and the coverage is considered insufficient for this to be studied further.

. . .

(Lines 158–184) From Fig. 2 we identify two distinct behaviors of RTOA. The first is a period of steepest decrease, from April to June, and the second is a plateau of relatively flat RTOA, between July and September. The changes in surface reflectance between April and May are attributed to snow cover changes and those in June to sea ice changes (Smith et al., 2020). Over water, the timing of such transitions increasingly approaches the summer solstice, which is the day of strongest solar insolation, while it moves further away from it over land (Letterly et al., 2018). It is therefore reasonable to regard this day as a demarcation point between Arctic spring and summer.

In summary, we group April May June (AMJ) as Arctic spring and July August September (JAS) as Arctic summer. This distinction is explained by the sensors' measurement strategy and by the time-dependent physical processes leading to the transition between high-to-low Arctic reflectance in June to the minimum sea ice extent in September. We note that the definition of seasons is arbitrary and is determined by the breakpoints of the variable under consideration. In general, seasons can be astronomical, meteorological or climatological. Provided that our study deals with two decades of data, meteorological seasons are not useful and are not discussed hereinafter. The astronomical seasons for the Northern Hemisphere are AMJ for spring and JAS for summer (Cannon, 2005). Climatological seasons can be defined ad-hoc, one example being the Indian monsoon season stretching beyond the customary breakpoints (Fasullo and Webster, 2003). In our case, the fundamental motivation for defining ad-hoc Arctic seasons is then to ensure that the computed trends describe only those changes of RTOA caused by distinct underlying processes, which in turn determine the breakpoints in the time series of RTOA shown in Fig. 2.

R20

Line 152; what do you mean by "individual downstream methodology"; downstream of what?

A20

Any geophysical algorithm, and related data set, is a "downstream methodology". The measured spectra, and related calibration activity, are the "upstream technology".

In the broad, and common, context of technological supply chains, **upstream** means the provision of a technology, while **downstream** means the exploitation of that technology.

Specific to our satellite and algorithmic realms, the sentence of our paper "individual downstream methodology" stands for "distinct algorithms, deployed by distinct research groups, using the same L1 data set (the provisioned technology) to create distinct L2 data (the geophysical parameter generated by the algorithm: the exploited technology)".

The context of these words is (and I quote lines 150–153 of the manuscript):

> "The primary reason for choosing these records is the abundance of studies using these data in the Arctic. This has the required coherent radiometric calibration before the implementation of individual downstream methodology to assess changes across the Arctic. The cloud and flux records, version 3, are presented by Stengel et al. (2020)."

In other words, our choice is driven by the maturity of the AVHRR data set of measurements, its popularity, and by the advanced, most recent, retrieval algorithm exploiting it. We will update the corresponding section.

C20

(Lines 191–193) One good reason for choosing this AVHRR record is the number of studies using these data in the Arctic. Our choice is driven by the maturity of the AVHRR data set of measurements, its popularity, and by its successful use by the advanced, most recent, retrieval algorithm exploiting it.

R21

What is an "aggregated IWP histogram" (line 157) and how is it different from any other IWP histogram?

A21

IWP retrievals are averaged by using the approach described in Stengel et al. (2015). IWP validation of aggregated histograms is described in Section 3.5 of Stengel et al. (2015) against the DARDAR data set. It is not a pixel-based validation, but a validation of IWP distributions, aggregated in space and time, instead. We will clarify this issue.

Stengel, M., et al. "The Clouds Climate Change Initiative: Assessment of state-of-the-art cloud property retrieval schemes applied to AVHRR heritage measurements." Remote Sensing of Environment 162 (2015): 363-379. `https://doi.org/10.1016/j.rse.2013.10.035`

C21

(Lines 207–210) While agreeing on the sorting of cloud tops between water and ice phases, higher variability for IWP values lower than 50 $\mathrm{g\,m^{-2}}$is found as compared to that in the reference DARDAR cloud data products (Delanoe and Hogan, 2010), but IWP histograms across the full range do not substantially differ (Stengel et al., 2015).

R22

The sentence “Broadband ... instead” (line 163-164) must be missing some words.

A22

The sentence at lines 163–164 reads: “Broadband fluxes are not derived by incorporating reanalysis data but tretrieved cloud properties instead.”

In other words: the algorithm ingests retrieved cloud properties and calculates broadband fluxes without using reanalysis data.

R23

Observations cannot be derived from models (line 185)

A23

We replace “observed by models” with “calculated by models”.

R24

and I for one cannot see the trends in Figure 4 (line 188); it may be there but it is not obvious from looking at the figure

A24

We quote line 188 of the paper that introduces Figure 4: “A small downward trend of reflectance for the three wavelengths in the solar range is seen in the anomalies of Fig. 4”. Alongside the fitted trend line, we report the function $F(T)$ in each panel:

$$F(T) = (\text{intercept} \pm \text{confidence}) + (\text{slope} \pm \text{confidence}) \times T, \text{ with } T = 10 \text{ years.}$$

All slope values are negative and do not exceed the 95% confidence interval threshold. This is one of our scientific findings : the spectral reflectance has slightly decreased and its trend is small. We will clarify this.

C24

(Lines 299-300) A negligibly small and statistically insignificant downward trend of RTOA for the three wavelengths in the solar range is seen in the anomalies of Fig.4

R25

and a change in one area cannot be “compensated” (line 203) by a change in another area.

A25

Because the sentence at lines 203–204 of the paper follows a section where trends in reflectance at pan-Arctic level are discussed, it is our intention to highlight the dipole nature of reflectance trends across the Arctic. Namely, the above mentioned pan-Arctic negligible trend is a result of the compensation of increasing and decreasing trends on a regional scale.

R26

On line 215-216 you "infer" things from changes in clouds without reference to what it is you actually do; the paragraph just ends with this statement.

A26

Coherent with the meaning of the word, we end the paragraph concluding with the deduction of a scientific concept from the facts explained in the previous lines.

R27

The red markers in Figure 6 are not mentioned in the fig caps

A27

The red markers are mentioned in the captions. This is exactly what the following sentence in the Figure's caption stands for: *"Stippling in red indicates significant trends at 95% confidence"*. The wording is not unusual in literature. See, for instance, the caption of Figure 4 and following in Rinke et al. (2019).

Rinke, A., et al. "Trends of vertically integrated water vapor over the arctic during 1979–2016: Consistent moistening all over?." Journal of Climate 32.18 (2019): 6097-6116.
`https://doi.org/10.1175/JCLI-D-19-0092.1`

R28

and the different parts of Figure 7 (that could benefit from breaking into two) are sometimes referred to as "upper" and "bottom" (line 233) panels and sometimes as "left" and "right" (fig caps).

A28

Agreed. We split Figure 7 in the manuscript and adapt the placement references accordingly.

R29

Changes in CTH are given in percent; is that wise? A 100 m change is a 100 m change and corresponding to roughly the same temperature change regardless of it is at 1 or 10 km, but the percentage change is quite different.

A29

This is appropriate when the parameter under consideration is only one, in this case cloud top altitude. We consider that it is a choice of convention and that we analyze changes of parameters of different physical meaning (reflectance, cloud properties, radiative forcing). Consequently, we consider the changes in % relative to the parameter's value at the beginning of the time series.
We have consistently adopted this convention from Figure 5 till the end of the paper to give the reader the ability to compare changes in different variables with a single yardstick.

R30

On Line 245 you discuss a decrease " especially where statistically significant"; is there any point in discussing changes that are not statistically significant?

A30

Yes, certainly. Statistical significance implies that the null hypothesis is not verified. In our case, the null hypothesis is that the variation of a parameter is within natural variability. This is also a result, especially when analyzing atmospheric quantities, for which the long-range modulation of recurring meteorological patterns may not be negligible.

R31

Conversely the change in CTH is once quoted to be 6 m; is that a difference you feel comfortable with give the measurement accuracy, statistically significant or not?

A32

Yes, certainly. Although the trend was computed from anomalies and not from absolute CTH values, such variation can be confidently considered to be negligeable over the considered period of measurement. This is exactly the message: the macro-physical properties of clouds (CFC and CTH) remained substantially unchanged, but not the optical properties (COT).

R33

On line 261-262 you discuss a change that is "marked" on spatial but not temporal scales, but what is a change if it is not temporal?

A33

We do not understand the referee's objection. A change can occur within several domains, these being spatial, temporal, phase, amplitude, velocity etc. It is not only in the temporal dimension. The sentence at lines 261–262 reads:

> "The rightmost polar plots of Fig. 7 show seasonal trends in cloud albedo (CA), for which a marked change of the spatial rather than temporal scale is observed."

Looking at Figure 7 in the manuscript, we see that the cloud albedo does not change strongly between seasons, also temporally, but rather shows a spatial change.

For the sake of clarity, we propose to improve the sentence with the following text.

C33

(Lines 384 – 385) The polar plots of seasonal trends in cloud albedo (CA) in Fig. 8 show that the magnitude of the positive trends in JAS is larger than those of AMJ but the spatial extent of the CA trend values are similar in both seasons.

R34

The whole section on CRF is very interesting and would benefit from knowing where this is; surface or TOA? By the way, what is BOA (Line 293); not in the list of acronyms.

A34

Table A1 at page 26 lists only the abbreviations of platforms, sensors, measurement campaigns and datasets. Geophysical and geometrical quantities or variables are described in the main text. Consistently, the acronyms TOA and BOA are defined in the main text at lines 32 and in the caption of Figure 1, when they first appear. BOA stands for "Bottom Of Atmosphere".

At the beginning of Section 3.2 on cloud radiative forcing it is clearly stated that:

> "The multi-year mean and trends of SW, LW and total CRF **at the surface** are plotted in Fig.9 " (line 280).

In the caption of Figure 9 it is clearly stated that:

> "For Arctic spring (AMJ, top) and summer (JAS, bottom), the multiyear mean Cloud Radiative Forcing (CRF) and total change ΔCRF **at the surface**.

The labels of the y-axis of Figure 10 clearly reads:

> "Mean CRF Total at **BOA**".

Strange Things Happening in the Frozen Arctic

Science Puzzled by Surprising News from the Far North Which Indicates That the Polar Sea Is Warming Up and the Great Ice Cap Is Slowly Melting Away Which May Soon Reveal the Hidden Secrets of the Unknown Polar Continent

Seals Leave Their Old Feeding Grounds Because the Water Is Too Warm and Vast Schools of Smelts Arrive Further North Than Ever Before, While Land Begins to Appear Which Has Always Been Covered by Ice

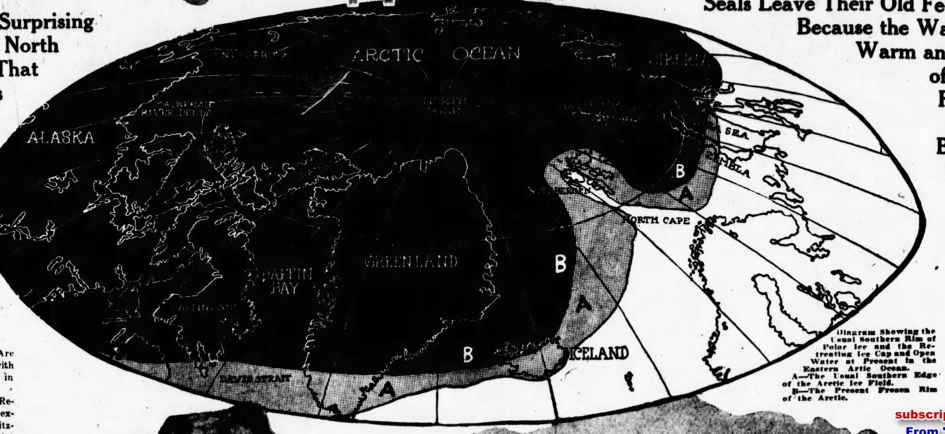


Diagram Showing the Usual Southern Rim of Polar Ice and the Retreating Ice Cap and Open Water at Present in the Eastern Artic Ocean.
A—The Usual Southern Edge of the Arctic Ice Field.
B—The Present Frozen Rim of the Arctic.

IS the North Pole going to melt? Are the Arctic regions warming up, with prospect of a great climatic change in that part of the world?

Science is asking these questions. Reports from fishermen, seal hunters and explorers who sail the seas about Spitzbergen and the eastern Arctic all point to a radical change in climatic conditions, with hitherto unheard-of high temperatures on that part of the earth's surface.

Observations to that effect have covered the last five years during which the warmth has been steadily increasing. In August of this year the Norwegian Department of Commerce sent an expedition to Spitzbergen and Bear Island under the leadership of Dr. Adolf Hoel, professor of geology in the University of Christiania, the object in view being to survey and chart areas productive of coal and other minerals. The expedition sailed as far north as 81 deg. 29 min. N. latitude in ice free water. Such a thing, hitherto, would have been deemed impossible.

The United States Consul at Bergen, Norway, Mr. Iff, has sent a report to our own Department of Commerce which speaks of the recent extraordinary warmth in the Arctic. He quotes incidentally the statements of Captain Martin Ingebrigtsen, a mariner who has sailed those seas fifty-four years. The captain says that he first noted an unusual warmth in 1918; and since then temperatures have risen steadily higher. To-day the eastern Arctic is "hardly recognizable as the same region of 1868 to 1917."

Many of the old landmarks are greatly altered, or no longer exist. Where formerly there were great masses of ice, these have melted away, leaving behind them accumulations of earth and stones such as geologists call "moraines." At many points where glaciers extended far into the sea half a dozen years ago they have now entirely disappeared.

The change in temperature has brought great changes in the plant life and animal life of the Arctic. Formerly vast shoals of whitefish were found in the waters about Spitzbergen, but last Summer the fishermen sought them in vain. Seals, which used to be plentiful in those seas, have almost entirely disappeared. It would seem as if the ocean must have become uncomfortably warm for some of its denizens which formerly frequented those latitudes, causing them to flock northward toward the Pole.

On the other hand, other kinds of fishes, hitherto unknown so far north, have made their appearance. Shoals of smelt have arrived, and immense schools of herring are reported by fishermen along the west coast of Spitzbergen

Formerly the waters about Spitzbergen have held an even Summer temperature in the neighborhood of 5 degrees above freezing. This year it rose as high as 28 degrees. Last Winter the ocean did not freeze over even on the north coast of Spitzbergen. This is on the authority of Dr. Hoel.

This state of affairs is a cause of much surprise and even astonishment to scientists, who wonder whether the change is merely temporary or the beginning of a great alteration of climatic conditions in the Arctic, with consequent melting of the polar ice sheet.

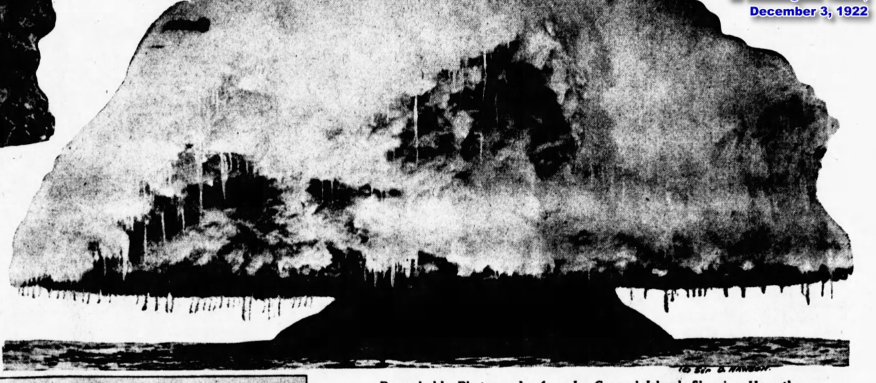
An evidence of how great the change is that has come over the climate in the Arctic regions may be best understood by the struggles of the early explorers to discover the northwest passage, or the open body of water existing around North America, leading eventually to India. This passage was first undertaken by way of Spitzbergen, but the thick ice repeatedly beat back the ships of the explorers.

From exploits to discover the northwest passage many of the trips for the conquest of the North Pole were eventually undertaken.

Parry, the great British explorer, was first to negotiate the open passage between Greenland and Bering Sea, reaching half-way across the top of North America before he was hedged in by the ice, and with supplies becoming low, dared go no further.

He was first to discover the north magnetic pole and to report the astonishing fact that the needle of his compass turned and pointed directly south. For these discoveries Parry was awarded about $25,000 by the British Government and unquestionably his conquests in the frozen Arctic led to the actual penetrating of the northwest passage from the Atlantic to the Pacific by McClure, Collinson and Amundsen later on.

Interesting Fossil of a Tropical Fern Dug Up in Greenland, Showing That There Was Once a Warm Climate and Tropical Vegetation Where the Glaciers Are Now Melting Away.



Remarkable Photograph of an Ice-Capped Island, Showing How the Warmer Polar Sea Is Melting the Ice.

Photo Underwood & Underwood.

Photograph of Land Which Has Appeared for the First Time in Greenland, and Which Has Always Heretofore Been Buried Under the Glaciers Which Are Now Melting Away.

From the difficulties besetting these great Arctic adventures some idea of the tremendous thickness of the ice may be had. Even at the very spot north of Spitzbergen where open water was seen this Summer, such well-known explorers as Hudson and Phipps had great difficulties in penetrating on account of the thickness of the ice and, in spite of their equipment, one of them could not go even as far over the ice as the spot where the open water showed a few months ago.

Not only are the seals and polar bears finding the climate unpleasantly warm for them, but it is said that the eskimos in some localities are complaining and are finding their fur clothes too warm for them.

The region about the North Pole is covered by an ice cap which, toward the east, extends over nearly the whole of Greenland in what is practically a single enormous glacier. Greenland is ten times the size of the State of Pennsylvania, and from its vast ice sheet are derived the icebergs which float down from Baffin Bay and Davis Strait into the North Atlantic, threatening destruction to ships in the Spring of every year.

To cross this great Greenland glacier has been the quest of many adventurous spirits. On account of the severity of the winds that sweep over the immense slowly moving cake of ice, it was never successfully accomplished until Nansen managed to go from the east coast of Greenland across the top of the ice barrier to the west coast at about the sixty-fourth parallel of latitude.

Nansen and his five companions reached a height of 8,922 feet at the top of the barrier, showing how thick the ice had become through ages of freezing.

Later on Peary and Astrup crossed the island much further north and had to climb a solid hill of ice about 8,000 feet high.

The reason why we have these icebergs sloughing off from the southeastern tip of Greenland is evidently due to the north polar current carrying the ice mass from the north polar region along the land and keeping it at a very low degree of temperature down to Cape Farewell, the southernmost tip of Greenland. Here, during the Summer, the oncoming of the warm weather disintegrates some of the ice, particularly between the fissures, which are characteristic of each year's ice growth. Here they are spilt and carried away by the polar currents into the North Atlantic where sometimes they become very dangerous to ocean shipping.

It is a singular fact, and true of only this spot in the world, that the cold polar current that sweeps down the Eastern coast of Greenland is paralleled not very far outside by a warmer current, which is largely responsible for a considerable amount of precipitation that in turn has it effect in wearing down some of the glacial ice and bringing about the eventual formation of icebergs.

But there was not always an ice cap. In time long gone by the region about the North Pole had a warm climate and all of Greenland was covered with a luxuriant tropical vegetation. This is positively known because fossil remains of palms, breadfruit trees, and other plants properly belonging to warm latitudes have been dug up there in quantities.

The present Polar ice cap is but a remnant of what it formerly was. Thirty thousand years ago it extended over all of the northern half of the United States, in places thousands of feet thick and reaching as far south as Philadelphia and St. Louis.

It was a product of the Glacial Epoch—an age of cold, during which polar bears and reindeer were numerous in New York State, and walrus and herds of the dwarf Arctic cattle called musk oxen frequented the coast of New England.

Since that time the great ice sheet has been slowly melting at the edges, so to speak, and withdrawing northward toward the Pole. It retreated past Stockholm (say the geologists) not more than 9,000 years ago. If the process continues, the day may be expected to arrive when all the ice will be gone from about the Pole, and the Arctic regions will then become fruitful and habitable by man.

It seems at least possible that the extraordinary warmth in the Arctic during the last few years marks a step in this direction. Such a change as that suggested cannot be suddenly or even rapidly accomplished; but, if there shall come a time when the North Polar ice cap is entirely melted, and Greenland incidentally freed of the ice sheet which covers it, the latitudes in which we now dwell will experience a wonderful climatic alteration. The northern part of the United States will become sub-tropical.

From what has been said it will be understood that we are really still living in the Glacial Epoch. It seems, however, to be drawing gradually toward a close; and it is easily possible to imagine that eventually all parts of the earth will become warm again, just as was the case at the period above referred to, when Greenland was covered wtih a luxuriant vegetation.

Nobody knows what causes produced the age of ice. It must have been that the sun, for some reason, delivered less heat upon the earth. Though hard for us to realize, it is a fact that if the average temperature of the northern half of the United States were lowered only ten degrees, the ice sheet would creep southward again and cover all that part of the country, sweeping its cities off the map and giving it a likeness to the Greenland of to-day. This would happen because the difference of ten degrees would make the Winters so much longer that the snows would not have time to melt in Summer, and so the ice sheet would thicken year by year until it became one vast glacier.

So it is just as well that we find ourselves approaching the end of an age of ice, instead of being menaced by its oncoming. It is fairly to be expected that from this time on—judging from observations of the retreat of the great ice sheet—climates all over the world will become steadily and gradually warmer. No longer ago than 200,000 years the climate of Greenland was still temperate, and Alaska had temperatures like those of Alabama nowadays.

Not long ago two government geologists, David White and Charles Schuchert, paid a visit of exploration to west Greenland, where, far north of the Arctic Circle, they studied a fossil flora of palms, tree ferns, breadfruit trees, cinnamon trees, etc., belonging properly to the neighborhood of the Equator. Where now an ice sheet over a mile thick covers mountain and valley and mighty glaciers make their way to the sea and hatch icebergs, there was anciently a wilderness of tropical verdure.

There were trees related to the giant sequoias of our own west coast. Climbing vines festooned the trunks of these monarchs of an ancient forest with draperies of foliage, while close to the ground grew curious dwarf trees called "cycads" resembling palms in miniature, in the midst of a tangled undergrowth.

Of such a character was the vegetation of Greenland 5,000,000 years or so ago. White and Schuchert found the tropical plant beds overlaid by later deposits in which were masses of fossil remains of trees, including poplars, willows, eucalyptus and magnolias. Much of this material had been converted into "brown coal," or lignite. This latter formation was relatively recent, dating back only to the Tertiary Epoch when the climate of Greenland was much like that of our Gulf States to-day.

At the far more ancient period when Greenland was a tropical country the climate seems to have been much the same all over the world, and the same plants grew contemporaneously in Greenland and California, in Spitzbergen and Virginia. Nobody can say with certainty why this was. One theory is that in that epoch the atmosphere was so heavily charged with water-vapor that warmth was readily distributed through it, and the sun's rays did not have a chance to strike the earth uninterrupted, making differences in climate by the degree of their slant. As time went on, the atmosphere thinned gradually, and so there came to be climatic variations marking a series of zones around the world.

Of the fact that the Polar regions were anciently warm and verdure-clad an interesting proof was afforded by a discovery which Greely, the explorer, chanced to make. Within eight degrees (latitude) of the North Pole he found a fossil forest with stumps of trees still standing.

Greenland is the largest island in the world. It is mainly a granite formation, but some of the less elevated portions of it were evidently at one time below the level of the sea—as is proved by sedimentary deposits. In these deposits White and Schuchert found plentiful remains of marine animals, including fishes and extinct species of crustaceans.

At the period when Greenland was a tropical country there grew in waters along the New England coast species of corals which to-day are found only in latitudes not far from the Equator. They afford another proof that anciently climatic conditions were altogether different from what they are at the present time.

It is worth mentioning, by the way, that Dr. Adolf Hoel reports, as one profitable result of the recent Norwegian expedition, the discovery of hitherto unknown coal deposits, of great extent and superior quality, near the eastern shore of Advent Bay, in Greenland. These deposits, of course, represent a profuse plant life which existed through a great length of time in a former epoch.

Scientists declare that there have been in the past several glacial epochs. Apparently, owing to causes unexplained, long periods of cold have alternated with long periods of warmth. The prospect seems to be that one of these periods of warmth, which may last tens of thousands or even hundreds of thousands of years, is approaching; and in the phenomena now exciting so much attention in the Arctic may perhaps be seen a promise of changes that will beneficially affect the entire population of the world, incidentally rendering available for human occupation vast land areas which are now uninhabitable.

Fig. 3: “Strange Things Happening in the Frozen Arctic”. American Weekly magazine, Washington Times, December 3, 1922.

Answer to Anonymous Referee #2, 20 April 2022

`https://doi.org/10.5194/acp-2022-28-RC2`

Structure of the document:

1. The remarks by the referee are black and labelled as $\mathrm{R}_{1\ldots n}$
2. Our answers are red and labelled as $\mathrm{A}_{1\ldots n}$. For each answer, we explicitly say how the text will be updated together with new figures, where appropriate.
3. Relevant non-trivial changes are verbatim reported in blue and labelled $\mathrm{C}_{1\ldots n}$ with the line numbers of the revised manuscript.

Before we delve into responses to the specific points raised by the referee, we want to thank him for taking the time to read our text in depth.

Summary:

This paper is an interesting assessment of satellite observations of trends in total albedo of the Arctic along with a number of other properties of the clouds that would impact that albedo. The topic is very relevant and timely, considering the rapid shifts occurring in the Arctic over the past couple of decades. Moreover, there is wide interest in understanding the potential contributions and feedbacks associated with clouds in the changing Arctic. The type of data used here is perhaps the only means for answering the questions that are posed. Thus, the topic and general approach are quite reasonable and worthy of publication. However, there are a number of major challenges with this paper that render it not publishable in its current form. The first of these is the lack of clarity in the writing. The introduction is a great example. It touches on important points and provides good references, but is generally not clearly written. As a person who has studied this field for many years, I was often confused by what was being stated. Some points are not entirely correct as stated and often the linking of one sentence to the next does not make sense. This lack of clarity is present through the rest of the manuscript (apart from the appendices, which happen to be quite clear). Heavy scientific editorial work is needed to clean up the writing, adjust sentence structure and wording choices, and to overall help make the points clear.

We inform the referee that the introduction has also been rewritten with referee#1's comments in mind, and the flow has been made clearer, logical and explicit. The section "Discussion and conclusions" has been split.

R1

Additionally, this work is focused on decadal trends that are often very small and, in most locations, not statistically significant. Thus, the whole analysis is really working on the margins of what is possible to conclude from the data sets that are employed. Yet there is very little effort put towards quantifying or characterizing the uncertainties that are inherent in the data used, as well as the implications of these uncertainties for the conclusions that are drawn.

A1

Certainly, some parameters do not show any trend in the time frame investigated. But this is not an handicap for the following three reasons:

1. We confirm that most of the non-significant or very small trends are at the pan-Arctic level. However, the breakdown in seasons and regions reveal concealed patterns and trends. Some of these trends are relatively large magnitudes and are statistically significant. In our analyses, we investigate pan-Arctic and regional trends. We consider that this enables the maximum information to be deduced from the spatial and temporal coverage of the space borne records available.
2. We are also convinced that observing a small trend, which is not statistically significant, is in itself an interesting result, provided that a deeper analysis is offered. Statistical significance implies that our null hypothesis is not verified. In our case, the null hypothesis is that the variation of a parameter is within natural variability.
3. With respect to the deficiency in quantifying the uncertainties for the three families of parameters used in the paper (i.e. reflectances, cloud properties, cloud radiative forcing), we provided respectively: **(A)** a detailed appendix explaining the methodology used to harmonize spatial (i.e. radiometry) and geometric sampling during the merging of three sensors on different platforms; **(B)** an appendix where we calculated, based on the pixel-level uncertainties, the error in averaging the cloud properties; **(C)** Comprehensive list of references to the verification and validation of satellite-derived broadband fluxes against in-situ stations.

Additionally, we have prepared a manuscript on the evaluation of the CCI cloud parameter data set, ready for submission, in which we validate retrievals of cloud properties (CTH, COT and LWP) by comparison with the measurements of these from ground-based measurements obtained from Arctic stations. We are happy to confidentially share this.

Lastly, the main point of the paper is cooling by "wetter clouds;" however, it has not been demonstrated that the clouds are actually wetter, and it might be that the clouds have simply shifted from more ice to more liquid water without a net change in mass. This point must be addressed.
Further, the decline in surface albedo alone will lead to a stronger effective "cooling" by the clouds, regardless of changes in the clouds. The importance of this point has not been appropriately addressed in the paper. Generally, there appear to be some misinterpretations of cloud radiative effects. Below there are many comments regarding these general critiques. I believe the core of the work is a good starting point, yet major revisions are needed to bring this manuscript up to the standards that are expected for publication.

Specific Comments:

R2

Line 36-37: This sentence is not clear to me. Perhaps: "the magnitude and variability of CFC depends on atmospheric conditions, cloud nucleation and growth, and the type of sensors used to measured it."

A2

Agreed. We have corrected the sentence as suggested.

R3

Line 37-38: I believe that the CFC of clouds (based on high-resolution data) is, in fact, bi-modal. This means that there is a relatively high occurrence of both high CFC and low CFC. However, this sentence appears to refer to the annual cycle of CFC. It appears that what you mean is that over the course of the year there are two relative maxima and two relative minima in CFC. If the later, please clarify and change the word bi-modal to something more appropriate. If I have mis-interpreted, please modify the sentence to be clearer.

A3

The referee's comment is correct. The U-shaped distribution of cloud fractional cover is well-known. We are not referring to this but to the yearly cycle instead. We will clarify this aspect.

C3

(Lines 48–51) The CFC annual cycle in the Arctic has two maxima. One occurs in summer, where CFC may be as large as 90% and is located in the North Atlantic and the circumpolar ocean waters. The second maximum of CFC, which is approximately 40%, occurs during the winter months (Eastman and Warren, 2010b, a; Boccolari and Parmiggiani, 2018).

R4

Line 46-47: While I am a huge fan of clouds, I'm not sure this is the case. Large scale circulation patterns are particularly important for "modulation of energy flow exchange between the Arctic and its surroundings." Clouds are more important for the local exchange but are not themselves necessarily that important for the link between the Arctic and its surroundings. This sentence would be true if it started: "Clouds are an important atmospheric factor....."

A4

The referee's comment is indeed correct. We will change the sentence accordingly.

R5

Line 50-51: Here it states that the change in surface reflectance from melting cryosphere is offset by changes in clouds. However, on lines 57-58 it is stated that this compensation does not occur. Which is it? It seems to me that this sentence could be modified to say: ".....relative changes in surface reflectance could be offset by atmospheric...."

A5

This is not the outcome of the study by Donohoe and Battisti (2011). We quote the relevant part of their conclusions:

> *The planetary albedo changes associated with global warming were found to be primarily due to changes in cloud albedo (93% of the intermodel spread). This result is unsurprising given that cloud albedo plays the dominant role in setting the planetary albedo in the unperturbed climate and that the surface albedo's impact on the TOA radiative budget is*

> *strongly attenuated (approximately threefold) by the atmosphere.*

Donohoe A. and Battisti D. S.: Atmospheric and Surface Contributions to Planetary Albedo, Journal of Climate, 24, 4402–4418, `https://doi.org/10.1175/2011JCLI3946.1`, 2011.

As for the contradicting message in lines 57-58, please refer to the next answer, where we combine the response to two similar comments by the referee.

C5

No change.

R6

Line 58: I don't understand the "thus levelling out the recent pan-Arctic reflectance trend" statement. It was just stated that the albedo trends are NOT compensated by changes in cloudiness. I think the second part of this sentence should simply be deleted.

A6

The referee, in his comment addresses one of the purposes of our introduction, namely to summarise the scientific findings in the literature, and contrast them where necessary, to point out the contradictions, that our research tries to reconcile.

Note that the lines 57–58 are followed by a reasoning where we point to possible sources of inaccuracy in the methodology devised by Pistone et al (2014).

Our intention is to point out that in the presence of a loss of brightness from the surface, Pistone et al. (2014) should have seen a leveling off of recent reflectance, due to a simultaneous increase in cloudiness. But this is not the case, due to the missing land areas in their analysis and the conversion from clear-sky to all-sky at the beginning of the record.

We will clarify this in the text.

C6

(Lines 73–78) In Pistone et al. (2014), a downward trend of all-sky albedo across the Arctic is reported. This is not compensated by an opposite trend in cloudiness, thus a levelling of the recent pan-Arctic reflectance trend. However, this analysis is limited to oceanic regions and additional uncertainties are caused by the conversion from clear-sky to all-sky albedo at the beginning of their record. As the clear-sky signal is derived from the sea ice record with sensors for which the atmosphere is almost entirely transparent, the all-sky albedo is computed with a post-hoc method adding the atmospheric part and is not the outcome of direct satellite measurements.

R7

Line 62-68: This summary of He et al. is quite confusing and should be rewritten to ensure that the points are clear.

A7

We will rephrase the results of He et al.

C7

(Lines 79–83) He et al. (2019) reports that the magnitude of the Arctic ice albedo feedback is locally dampened by clouds. Although a CFC increase is detected over some areas of frozen surface, only the negative correlations between clouds and retreating sea ice are statistically significant. This implies that over the marginal sea ice zones of transitional albedo (e.g. of the Beaufort Sea throughout the Laptev Sea) enhanced cloud cover effectively compensates the decrease of Arctic albedo at TOA, arising from the loss of sea ice

R8

Line 69-76: Again, it is hard for me to following the train of thought in this paragraph. Also, is it not obvious that "temperature-related processes dominate the Arctic warming"? Lastly, clouds only "amplify warming in the Arctic region" under certain conditions of sun angle and surface albedo; under other conditions they dampen the warming.

A8

There seems to be a misunderstanding about the sentence, as also pointed out by the first referee too.

We have not written "temperature dominates the Arctic warming". We have written "Temperature-related processes dominate the Arctic warming" instead. The difference lies in the distinct response of different processes to an increase in temperatures, as described in Pithan and Mauritsen (2014) and to a large number of micro-physical processes in cloud physics, that can be of opposite sign and different magnitudes as function of temperature. We will correct and improve this sentence as follows, bearing in mind that it is an introductory paragraph.

Please see A15, A47 for the dependency of CRF on solar zenith angle and A37 for surface albedo.

C8

(Lines 87–97) For example, with the increase of Arctic temperatures, the thermodynamic equilibrium between water vapor, liquid water and ice is altered, which imbalances the phase of clouds in presence of aerosol particles (cloud condensation nuclei - CCN - or ice nucleating particles - INP). Dependent on the cloud phase, the particle radius changes: liquid droplets being typically smaller than ice crystals (Mioche et al., 2017). This in turn affects the average optical thickness of clouds. The liquid and ice phases in the clouds interact differently with radiation in the solar and in the terrestrial spectral range. Already early studies (Curry et al., 1996) stressed that the additional presence of an underlying cold, bright surface and frequent temperature inversions impact atmospheric radiation budget through processes involving water condensate in form of liquid and ice clouds as a function of temperature profile. In a warming Arctic, it is expected that clouds will increase their liquid water content and thus reflect more SW radiation (Boisvert and Stroeve, 2015; Ceppi et al., 2016; Cesana and Storelvmo, 2017).

Curry, J.A., Schramm, J.L., Rossow, W.B. and Randall, D. Overview of Arctic cloud and radiation characteristics. Journal of Climate, 9(8), pp.1731–1764, 1996

Cesana, G., and Storelvmo, T. (2017), Improving climate projections by understanding how cloud phase affects radiation, J. Geophys. Res. Atmos., 122, 4594–4599, `doi:10.1002/2017JD026927`.

Boisvert, L.N. and Stroeve, J.C.. The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. Geophysical Research Letters, 42(11), pp.4439–4446, 2015.

R9
Line 77: Warming does not occur as a result of the release of greenhouse gases. Rather, there is warming due to an increased concentration of greenhouse gases in the atmosphere.

A9
We will correct the sentence accordingly.

R10
Line 77-78: The physical properties of clouds contribute to the tropospheric thermal emission. No need for "may" in this sentence.

A10
We will improve the sentence accordingly.

R11
Line 79: LWP/IWP is not the same as liquid/ice water content. One is an integral of the other. Please use the correct terminology.

A11
The referee is correct. We shall correct this accordingly.

R12
Line 78-80: These properties regulate the LW as well as the SW. And this point is important because later in this paragraph it is stated that changes in cloud properties enhance or suppress CRF at the surface. Part of their ability to enhance or suppress is related to the balance of LW and SW effects from clouds, in addition to other factors.

A12
The comment is correct and important. As it will also be part of the discussion section of this paper, we shall add the information in this part of the paper.

R13
Line 112-116: There is a list of criteria given here. These should be all included as a list and separated by semi-colons so it is clear what is part of the list and what is not part of the list.

A13
We agree and plan to update the punctuation marks accordingly.

R14
Line 134: The darkening of the Arctic is possibly apparent during some months in spring at some

wavelengths. But there is an even larger "brightening" of the Arctic in other months (mostly winter). First, it is not clear how this is the case with very little light in those months. Second, why is that feature not discussed in this paper, either as having importance for the geophysical system or as some indicator of uncertainty in the data stream?

A14

Our study is limited to the months of April to September (both included) and the winter months are excluded.

Lines 87–90 of the introduction read: "*A key set of satellite sensors record backscattered radiation in the solar portion of the spectrum. Consequently, this study focuses on the months between April and September.*"

Features beyond the time window April - September are not discussed because **(1)** we do not have enough radiation at $\lambda < 4$ µm available (as pointed out by the referee) and **(2)** because the sensors do not have all the same spatial coverage closer to the North Pole. Figure 2-c in the manuscript shows that we have guaranteed homogeneous coverage by the three sensors (GOME, SCIAMACHY and GOME-2) only up to the 85 N parallel.

We set this common latitudinal threshold exactly to avoid uncertainties in the data stream. In summary, we do not have sufficient coverage with these sensors to deem as real the "brightening" of the Arctic in the winter months and we refrain from such inferences.

We report here below the updated paragraphs.

C14

(Lines 157–167) While the measurement of solar radiation scattered back to the TOA by GOME, SCIAMACHY or GOME-2 takes place only during daylight, radiation in the thermal infrared ($\lambda \geqslant 4\ \mu$m), required to record the thermal emission from the surface and the atmosphere, is not measured by these sensors. Because of the different sensors' swath widths, the RTOA measurements in the solar spectral range have a northern latitude boundary (or terminator). This boundary is illustrated by plotting the pan-Arctic annual cycle of RTOA in Fig. 2. At the three wavelengths 510, 560, and 760 nm, the seasonality shows that summer months have lower RTOA and higher otherwise. This darkening of the Arctic can also be seen by comparing the years at the beginning of the record, 1996, with the most recent ones. However, this behaviour occurs only between April and September. These are the months when the individual terminator of the three sensors reaches the latitude 85 N, this being the spatial threshold of common spatial coverage we set in the monthly average. As shown in Fig. 2, the other months (October to March inclusive) show that recent years are brighter (higher RTOA) than those at the beginning of the time series. This is because the individual terminators move further south (Fig. 2-c) and the coverage is considered insufficient for this to be studied further.

R15

Line 162-163: This statement suggests that broadband fluxes are computed using cloud properties. However, little information is provided on how these broadband flux derivations are made. There are naturally many inputs and assumptions to such a calculation so it is difficult to assess the validity of this approach with the information provided. Even with more information, derivation of radiative fluxes from satellite measurements, particularly at the surface, is a challenging process and multiple studies have shown significant uncertainties. It is essential to 1) describe what techniques have been used, 2) describe the uncertainties inherent in those techniques, and 3) discuss how those uncertainties impact the results that are presented.

A15

We will add the following text to the manuscript. We blend the part on solar zenith angle with the concepts provided later on in A47.

C15

(Lines 212–254) The broadband fluxes for the solar and IR part are computed solving the radiative transfer combining the two-stream approximation by Stephens et al (2001) for the bulk bidirectional reflectance, transmission and source terms within a plane-parallel atmospheric slab and the spectral band model by Fu and Liou (1992) for gaseous absorption. Six bands in the SW and and 12 bands in the LW are calculated sequentially ingesting local properties of clouds retrieved with a Bayesian technique (Sus et al. 2018, McGarragh et al. 2018), which provides estimates of the individual uncertainty at pixel-level (see App. C). Specifically, effective radius and cloud optical thickness are the primary inputs for flux calculations together with solar zenith angle and ancillary data from MODIS climatologies of visible and near-infrared surface albedo, linearly interpolated to each spectral band centre. Local vertical atmospheric profiles from ERA-interim account for the p-T variations, while constant aerosol optical depth of 0.05 and concentrations of well-mixed gases are assumed, the latter being linearly interpolated for their time-dependent increase. The combination of the above factors yields an accuracy of $\pm 0.3\ \mathrm{W\,m^{-2}}$in outgoing LW radiation (Christensen et al, 2016). The physical boundaries of clouds are additionally required to correctly compute scattering and absorption along the vertical. From the retrieved CTH and effective radius, the bottom cloud layer is calculated assuming a subadiabatic variation of cloud water path, separately for the liquid and ice phases. While this approach is appropriate for the shallow case (Merk et al. 2016), the thickness of deeper clouds is computed combining a variable increase of water content matching within-cloud temperature profiles. The nominal accuracy limit in this case is reached at temperatures less than 217 K (-56 °C), which exceeds the yearly climatological range for the Arctic (-25 °C February, $+2.5$ °C July, Hersbach et al, 2020), and AVHRR-derived CBH is found to be in good agreement within ± 369 m against ceilometer observations (Meerkotter and Zinner, 2007).

Radiative transfer is solved twice. First all-sky fluxes are calculated with retrieved cloud properties and then the clear-sky fluxes, assuming that the pixel is devoid of clouds. This approach is in contrast to that employed with the MODIS cloud record and the CERES-EBAF radiation measurements at TOA, by virtue of which the interpolation of the measured clear-sky pixels serves as gap filling of all-sky pixels for the monthly aggregation of fluxes at BOA (Kato et al. 2013). AVHRR-derived fluxes at BOA have been validated by comparison with BSRN stations and the CERES-EBAF product (Stengel et al, 2020, ESA PVIR, 2020).

While on average comparisons with BSRN measurements show a good agreement for all downward fluxes and LWup, in some locations AVHRR-based estimates tend to be biased high for SWup $< 100\ \mathrm{W\,m^{-2}}$while the opposite holds for SWup $> 250\ \mathrm{W\,m^{-2}}$. This bias of higher spread can be due to the surface heterogeneity around the validation site, which influences the comparison of SWup because of the difference in spatial scales between the satellite footprint and the BSRN effective point measurement. The surface treatment in the satellite record is also a potential source of error because SWup is equal to SWdn times the surface albedo. While the actual sea ice extent is taken from measurements in the microwave (Henderson el al. 2013), a fixed value of surface albedo is assumed throughout

the record. Consequently, intra-annual variability and long-term changes of surface reflectivity are not accounted for. This would lead to underestimate actual surface albedos in those months having fresh snow and ice (spring) and to overestimate during months of melting surface upper layers (summer). Cloud radiative forcing is dependent on fluxes at the surface. In the case of underestimation of surface albedo (or sea ice extent) we expect an overestimation of CRF and thus warming by the clouds and viceversa.
We do not expect differences in BOA fluxes as function of solar zenith angles because the instantaneous fluxes are corrected for the diurnal cycle of solar illumination by adjusting the surface albedo and the atmospheric path lengths (Stengel et al, 2020). The LW fluxes have been also corrected by using a cosine function derived from measurements of the geostationary SEVIRI sensor. The final aggregation is a good approximation to a true 24h average, needed to determine the true climatological mean of SWand LW fluxes and thus CRF. Consequently, also the seasonal averages (i.e. AMJ and JAS) do not exhibit variation induced by solar zenith angle and directionality of surface reflection.

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Fu, Q., and K-N. Liou, 1992: On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres. J. Atmos. Sci, 49 , 2139–2156.

Sus, O., Stengel, M., Stapelberg, S., McGarragh, G., Poulsen, C., Povey, A. C., Schlundt, C., Thomas, G., Christensen, M., Proud, S., Jerg, M., Grainger, R., and Hollmann, R.: The Community Cloud retrieval for CLimate (CC4CL) - Part 1: A framework applied to multiple satellite imaging sensors, Atmos. Meas. Tech., 11, 3373–3396, `https://doi.org/10.5194/amt-11-3373-2018`, 2018.

McGarragh, G. R., Poulsen, C. A., Thomas, G. E., Povey, A. C., Sus, O., Stapelberg, S., Schlundt, C., Proud, S., Christensen, M. W., Stengel, M., Hollmann, R., and Grainger, R. G.: The Community Cloud retrieval for CLimate (CC4CL) – Part 2: The optimal estimation approach, Atmos. Meas. Tech., 11, 3397–3431, `https://doi.org/10.5194/amt-11-3397-2018`, 2018.

Christensen, M. W., Poulsen, C., McGarragh, G., and Grainger, R. G.: Algorithm Theoretical Basis Document (ATBD) of the Community Code for CLimate (CC4CL) Broadband Radiative Flux Retrieval (CC4CL-TOAFLUX) module, ESA Cloud CCI, available at: `http://www.esa-cloud-cci.org`, 2016

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Hersbach, H, Bell, B, Berrisford, P, et al. The ERA5 global reanalysis. Q J R Meteorol Soc. 2020; 146: 1999–2049. `https://doi.org/10.1002/qj.3803`, 2020

Stengel, M., Stapelberg, S., Sus, O., Finkensieper, S., Wuerzler, B., Philipp, D., Hollmann, R., Poulsen, C., Christensen, M., and McGarragh, G.: Cloud_cci Advanced Very High Resolution Radiometer post meridiem (AVHRR-PM) dataset version 3: 35-year climatology of global cloud and radiation properties, Earth System Science Data, 12, 41–60, `https://doi.org/10.5194/essd-12-41-2020`, 2020.

Kato, S., Loeb, N. G., Rose, F. G., Doelling, D. R., Rutan, D. A., Caldwell, T. E., Yu, L., and Weller, R. A.: Surface Irradiances Consistent with CERES-Derived Top-of-Atmosphere Shortwave and Longwave Irradiances, J. Climate, 26, 2719-2740, `https://doi.org/10.1175/JCLI-D-12-00436.1`, 2013.

Merk, D., Deneke, H., Pospichal, B., and Seifert, P.: Investigation of the adiabatic assumption for estimating cloud micro- and macrophysical properties from satellite and ground observations, Atmos. Chem. Phys., 16, 933–952, `https://doi.org/10.5194/acp-16-933-2016`, 2016

Henderson, D. S., L'Ecuyer, T., Stephens, G., Partain, P., and Sekiguchi, M. (2013). A multisensor perspective on the radiative impacts of clouds and aerosols. Journal of Applied Meteorology and Climatology, 52(4), 853-871.

Riihelä, A., J. R. Key, J. F. Meirink, P. Kuipers Munneke, T. Palo, and K.-G. Karlsson (2017), An intercomparison and validation of satellite-based surface radiative energy flux estimates over the Arctic, J. Geophys. Res. Atmos., 122, 4829–4848, `doi:10.1002/2016JD026443`.

R16

Line 164-167: I assume that these values for F (LW, SW, +, -) are at the surface since you cite comparisons with BSRN measurements.

A16

Yes. We will add the information.

R17

Line 173-174: This sentence needs to be rewritten for clarity.

A17

It is not clear to us how the sentence can be improved. The sentence at lines 173–174 (**boldface**) completes the information given at lines 170–173 :

> *The conversion of directional radiance, measured at TOA, to irradiance requires the knowledge of the angular light redistribution function of the surface and atmospheric components.* **If this is not accurately assumed, the irradiance and F$_{SW}^{+/-,clr}$ above reflecting surfaces cannot optimally be calculated**.

C17

(Lines 257–260) The conversion of directional radiance, measured at TOA, to irradiance requires the knowledge of the angular light redistribution function of the surface and atmospheric components. If this conversion is not accurately performed, the irradiance and SW$_{clr}^{+/-}$ above reflecting surfaces cannot optimally be calculated.

R18

Line 174-175: The text here has not really provided justification for the suitability of AVHRR cloud property retrievals for use in this paper. The prior statement simply says (I believe) that Philipp et al. showed that the trend in CRF has a low sensitivity to biases in cloud properties. This is different than saying that the cloud properties are suitable. The preceding statements also have not provided justification for how suitable the satellite retrieved cloud properties are.

A18

Philipp et al. (2020) do not only show that the "*CRF trend has a low sensitivity to biases in cloud properties*", as mentioned by the referee. If this were the case, we would certainly agree with him.

Philipp et al. investigate the biases in cloud radiative forcing (CRF) trends at the surface due to potentially inaccurate cloud fractional cover (CFC, also termed cloud masking, which is the most important quantity and a key input to a cloud retrieval algorithm) as a function of sea ice concentrations (SIC) between 0% (e.g. open waters) and 100% (fully sea-ice covered satellite pixels)
In our paper, we introduce the topic with the sentence on lines 168–169: "*Misclassified cloudy scenes especially over dynamically bright surfaces (i.e. marginal and fractional sea ice zones) impact the calculation of broadband fluxes.*"

The assessment of whether CRF trends are affected by misclassified cloudy scenes above bright surfaces exactly addresses the question of whether the data record is suitable for Arctic studies. For a more in-depth justification about the concern raised by the referee, please refer to the bullet list in the next answer A19 (especially bullet 4).

As a side note, the paper by Philipp et al. is titled "Analyzing the **Arctic** Feedback Mechanism between Sea Ice and Low-Level Clouds Using 34 Years of Satellite Observation" and the authors use the very same cloud data record we analyze. In summary we conclude that the AVHRR cloud record is suitable for Arctic studies of cloud parameters.

C18

Changes relevant to R18 are conflated with C19. Note that C19 is made by two paragraphs. The first introduces the revised section 2.2 "Cloud and flux data products" and the second closes it.

R19

Moreover, there are numerous papers documenting how AVHRR derived cloud properties have large uncertainties. Thus, further justification for the utility of the derived cloud properties is needed here. Specifically, it is important to describe how the uncertainties in the cloud products impact the analysis conducted here.

A19

We will update the manuscript with a digest of the following text, which describes the features of the algorithm relevant to the aim and scope of our work.

The main factors hindering the generation of an accurate Arctic cloud record from AVHRR data and its exploitation for the assessment of cloud properties trends in the past were **(1)** a poor account of the surface signal; **(2)** a poorly radiometrically calibrated AVHRR channels; **(3)-(4)** the usage of AVHRR channels, whose radiometric response drifts in time. These are the customary culprits for any cloud retrieval algorithm exploiting radiometric sensors.

We address each of these points here below, providing the evidence that the cloud record we use is appropriate and an improved reprocessing compared with previous AVHRR cloud records.

(1) AVHRR cloud mask is NN-trained on CALIOP surface mask (which is the gold standard in spaceborne research), and in-cloud extinction profiles are corrected with CALIOP profiles.

(2) AVHRR channels in the solar spectral range have been cross-calibrated with SCIAMACHY channels. SCIAMACHY is recognised for its accurate radiometric and spectral calibration.

The first author (Luca Lelli) has personally helped the record creator (ESA-DWD) in this task (see `https://essd.copernicus.org/articles/12/41/2020/#section11`).
This strengthens the meaningfulness of our results, because the part of our study dealing with TOA reflectances is conceived in a way that the record is radiometrically coherent with SCIAMACHY (see Appendix A). Even more important, note that in the AVHRR cloud retrieval algorithm the values of cloud optical thickness are retrieved from AVHRR in the same spectral range as SCIAMACHY. This implies that any reflectance change for SCIAMACHY visible channels is present in the AVHRR-calibrated radiance ingested in the cloud retrieval algorithm.

We make use of the Post-Meridiem (PM) AVHRR series and not the Ante-Meridiem (AM) AVHRR series. During the preparation of the manuscript we have quality-checked the time series of all cloud parameters and broadband fluxes above the Arctic used for the generation of our results. We found that the AVHRR PM dataset fulfilled the calibration stability requirements which allows trends' assessment to be made.

We share here below the respective time series of used cloud properties (Fig. 1) and broadband fluxes (Fig. 2) for both AM and PM AVHRR series. It is straightforward to see that the AM record (red lines, left column in the Figures) is prone to calibration offsets, whereas the PM series is not, for the NOAA-12 platform before 2003 due to continuous drifts and change of local overpass times and to data gaps for NOAA-15 due to scan motor errors. This is confirmed in the validation report by ESA (ESA Cloud_cci, 2020).

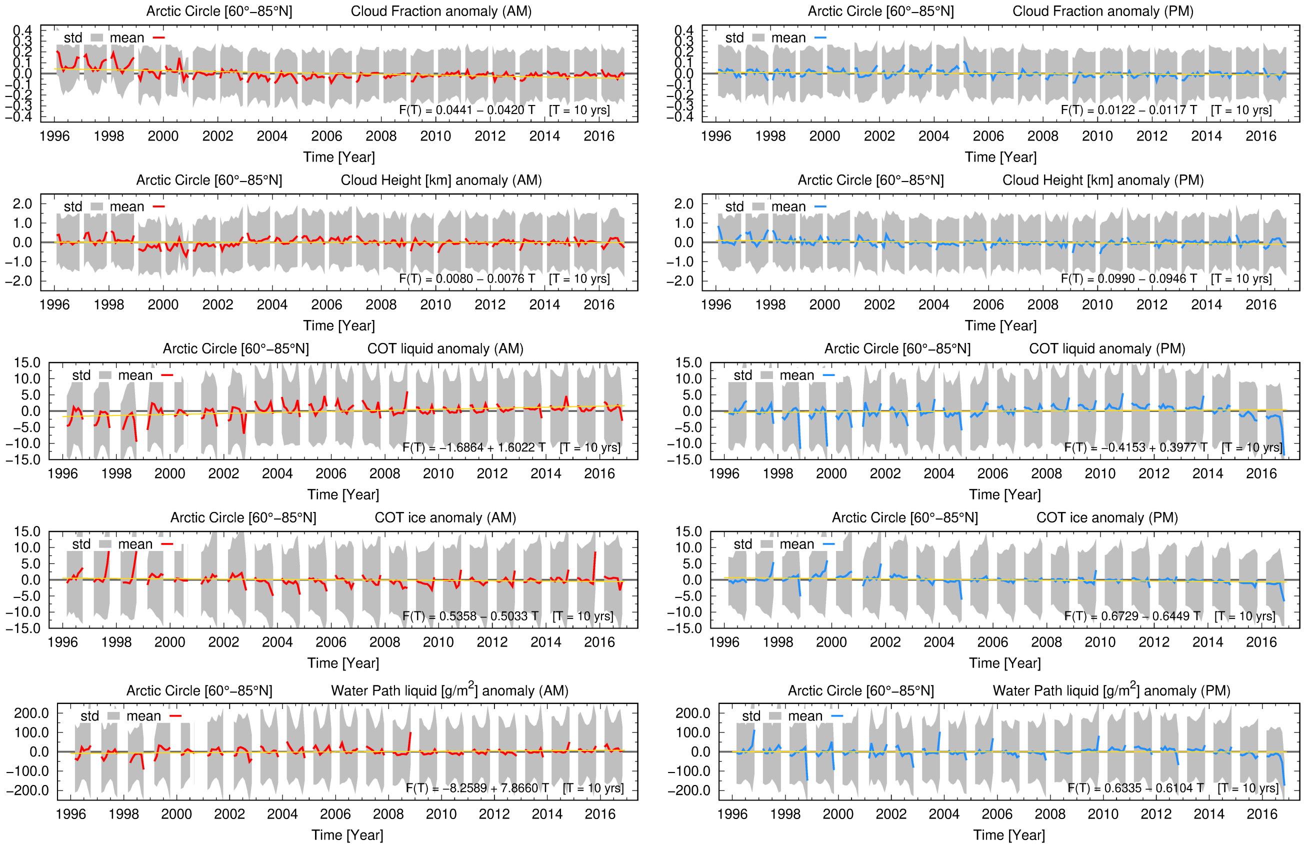

Fig. 1: Time series of those cloud properties used in our work for the AVHRR AM (left) and PM (right) series. From top to bottom: cloud fractional cover (CFC), cloud top height (CTH), cloud optical thickness of liquid clouds (COT liquid), cloud optical thickness of ice clouds (COT ice), liquid water path (LWP). Please note the suboptimal calibration of the AM series, especially at the beginning of the record (1996-2001), which impacts fluxes in the same time span (see Fig. 2).

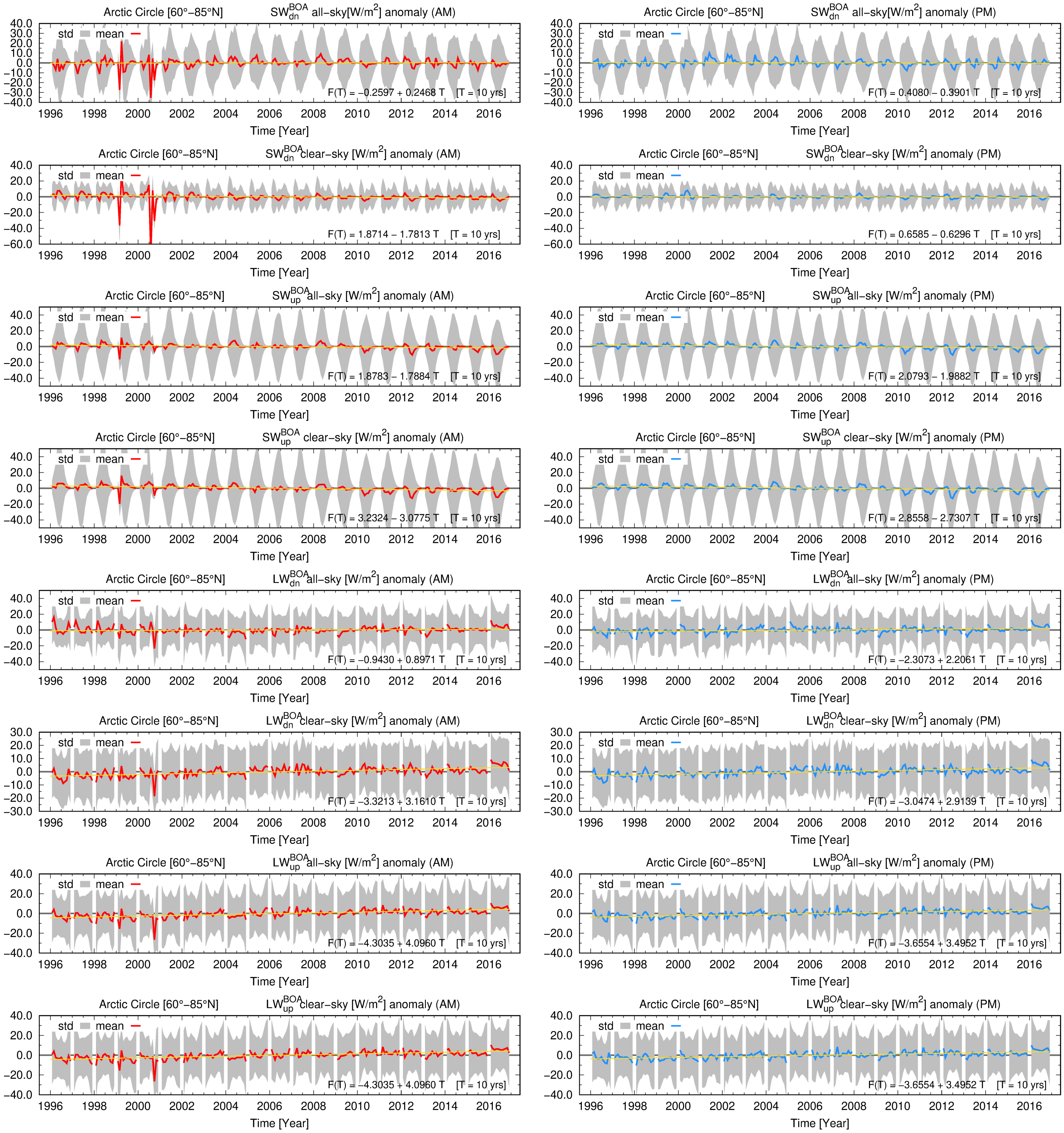

Fig. 2: Time series of broadband fluxes at the surface used in our work for the computation of cloud radiative forcing. For the AVHRR AM (left) and PM (right) series, we have (top to bottom): shortwave (SW) all-sky downwelling (DN), SW clear-sky DN, SW all-sky upwelling (UP), SW clear-sky UP, long-wave (LW) all-sky DN, LW clear-sky DN, LW all-sky UP, LW clear-sky UP. Please note the suboptimal calibration of the AM series, especially at the beginning of the record (1996-2001), corresponding to the ill-posed cloud properties of Figure 1 in the same time span.

(3) Irrespective of the verification and validation of the cloud record carried out by the data creators and documented throughout the traceable reports available at

1. `https://climate.esa.int/en/projects/cloud/key-documents/`
2. `https://climate.esa.int/media/documents/Cloud_Product-Validation-and-Intercompa`
   `v6.0.pdf`

we have independently validated the cloud record over the Arctic. The results are meant for a separate publication which is going to be submitted to AMT. In case of interest, we will be happy to share the draft with the handling editor and the referee.

(4) Figure A1, p7498, in Philip et al. (2020) shows CFC biases as function of sea-ice concentrations (SIC) for the seasons analyzed in our paper (i.e. AMJ is top right, JAS is bottom left).

For season AMJ, the bias is systematically flat from SIC 0% to SIC 100%.
Given that our trend model is based on anomalies and not absolute values, any additive component of the bias cancels out and the resulting trend is not affected by it.

For season JAS, the bias is not flat.
Because the SIC bins of Fig. A1 in Philipp et al. represent the SIC variance over one location in time, this effect is relevant only for those locations with a large dynamic in SIC (e.g. the marginal sea-ice zone).
Other said: the CRF trend is affected if the SIC anomalies in the record drift in time, e.g. their PDF is not Gaussian but skewed. This would be the multiplicative component of the bias in cloud cover adding up differently as we progress in time, thus propagating into the CRF trend.
Looking at Fig. 8, p 7489, of Philipp et al. (2020), the SIC anomalies for the marginal sea-ice zone of the illustrative enlarged Chuckchi Sea are plotted. We note that the SIC anomalies are normally distributed. If the SIC anomalies would drift in time, thereby adding the time-dependent component in the CRF trend via CFC, then the PDF at the bottom right of Figure 8 would be skewed. In this case the biases of Fig. A1 for JAS would definitively introduce a multiplicative component in CFC and the noise component would not be gaussian anymore (e.g. randomly distributed as white noise) but would contain a latency part. Our trend model would account for this computing the length of the effective independent sample in the record (see App. A).

The authors (Philipp et al.) conclude (and we quote):

> *However, TCRF (Total CRF) trends remain strongly positive over the whole ice pack and most of the melting zones. The correction demonstrates that observed ON warming trends are not vanishing - that is, that* **these trends are not the result of limited cloud detection capabilities of passive imagers** *when observing melting sea ice surfaces.*

Philipp, D., Stengel, M., and Ahrens, B.: Analyzing the Arctic Feedback Mechanism between Sea Ice and Low-Level Clouds Using 34 Years of Satellite Observation, Journal of Climate, 33, 7479–7501, `https://doi.org/10.1175/JCLI-D-19-0895.1`, 2020.

European Space Agency, Cloud_cci, Product Validation and Intercomparison Report (PVIR), Issue 6, Rev 1, https://climate.esa.int/media/documents/Cloud_Product-Validation-and-Intercomparison-R v6.0.pdf, 2020.

C19

(Lines 185–204) In our study, the RTOA data is complemented by a record of cloud properties and broadband fluxes at TOA and BOA. These are inferred from the afternoon orbit (PM) of AVHRR sensors onboard the POES missions. In spite of the availability of the morning orbit (AM) AVHRR series, we found that only the AVHRR PM series fulfilled the calibration stability requirements which allows trends' assessment to be made. Inspection of the time series of cloud properties and fluxes for the AM series showed that the drifts of the NOAA-12 platform before 2003, changing local overpass times, lead to calibration offsets and that the scan motor errors of the NOAA-15 platform to data gaps (Cloud_CCI Working Group, 2020). One good reason for choosing this AVHRR record is the number of studies using these data in the Arctic. Our choice is driven by the maturity of the AVHRR data set of measurements, its popularity, and by its successful use by the advanced, most recent, retrieval algorithm exploiting it. This AVHRR data set is in its 3rd reprocessing and the algorithm used to generate it has 15 years of development starting with ATSR-2 onboard ERS-2. While improvements and validation have been documented in traceable documents (https://climate.esa.int/en/projects/cloud/key-documents/), the cloud and flux records are presented by Stengel et al. (2020, and references therein). Some features, that distinguish this data record from older AVHRR records, are as follows: i) the channels in the solar spectral range have been cross-calibrated with SCIAMACHY channels. SCIAMACHY is recognised for its accurate radiometric and spectral calibration. Because the part of our study dealing with RTOA is conceived in a way that the record is radiometrically coherent with SCIAMACHY (see App. A), this intra-band correction relates reflectance changes at visible wavelengths detected by SCIAMACHY to those by AVHRR, ingested in the cloud retrieval algorithm, which calculates τ and cloud albedo; ii) the cloud mask uses a neural network, trained on CALIOP data to take into account the extent of the underlying bright Arctic surface; iii) CTH has been calibrated using CALIOP profiles to account for the penetration depth of radiation inside a cloud. This is needed because the retrievals of CTH from all infrared thermal channels are influenced by this effect and yield a radiative cloud top height, lower than the physical cloud top.

. . .

(Lines 260–273) Using the same data of our study, it has been found a low sensitivity of trends in cloud radiative forcing to the biases in cloud properties over surfaces of changing brightness (App. d in Philipp et al., 2020, p. 7499). Specifically, Philipp et al. (2020) assessed possible uncertainties in CRF trends analysing CFC biases as function of sea ice concentrations (SIC) for the seasons of our paper. For season AMJ, the bias is systematically flat from SIC 0% to SIC 100%. Given that our trend model is based on anomalies and not absolute values (see App. B), any additive component of the bias cancels out and the resulting trend is not affected by it. For season JAS, the bias is not flat and a multiplicative bias in CFC can propagate to CRF via SIC changes. However, the SIC bins of Philipp et al. (2020, Fig. A1) can also be regarded as the SIC variance over one location in time, therefore this effect is relevant only for those locations with a large dynamic in SIC (e.g. the marginal sea ice zone). If the SIC anomalies over one location in the marginal sea ice zone are not equally distributed about zero, irrespective of any trend, but progressively change over time, their distribution is not Gaussian but skewed. This leads to add the time dependent component in the CRF trend via CFC. Looking at Philipp et al. (2020, Fig. 8) the SIC anomalies for the marginal sea ice zone of the enlarged Chuckchi Sea are normally distributed. Upon regression, any possible residual of a non-normal SIC distribution, reflected in CFC and propagating into CRF, would still be captured by the trend model (see App. B) which accounts for the length of the effective independent sample in the record.

R20

Line 181-182: I do not know what this sentence means: "Any errors are minimized, when sunlight availability across the Arctic provides full coverage for the sensors' swath at highest latitudes." Does this mean that the errors are smallest when the sun is highest? Does this mean that there was a process in place (bias correction) to ensure that the errors are minimized at high sun angles? Something else?

A20

The sentence refers to the bias correction section in Appendix A. We are not making any claims of geophysical significance regarding possible errors as a function of the sun elevation. What is important for the quality of the reflectance measurement is that the portion of the solid angle covered by the sensors during the time windows used for averaging of data does not change with time (see Fig. 3). This ensures that the trends in reflectances are not contaminated by spurious trends due to extreme shifts in observation geometry, which would imply a different angular sampling of the phase function of surface and clouds (see Fig. 4).

We remove the sentence.

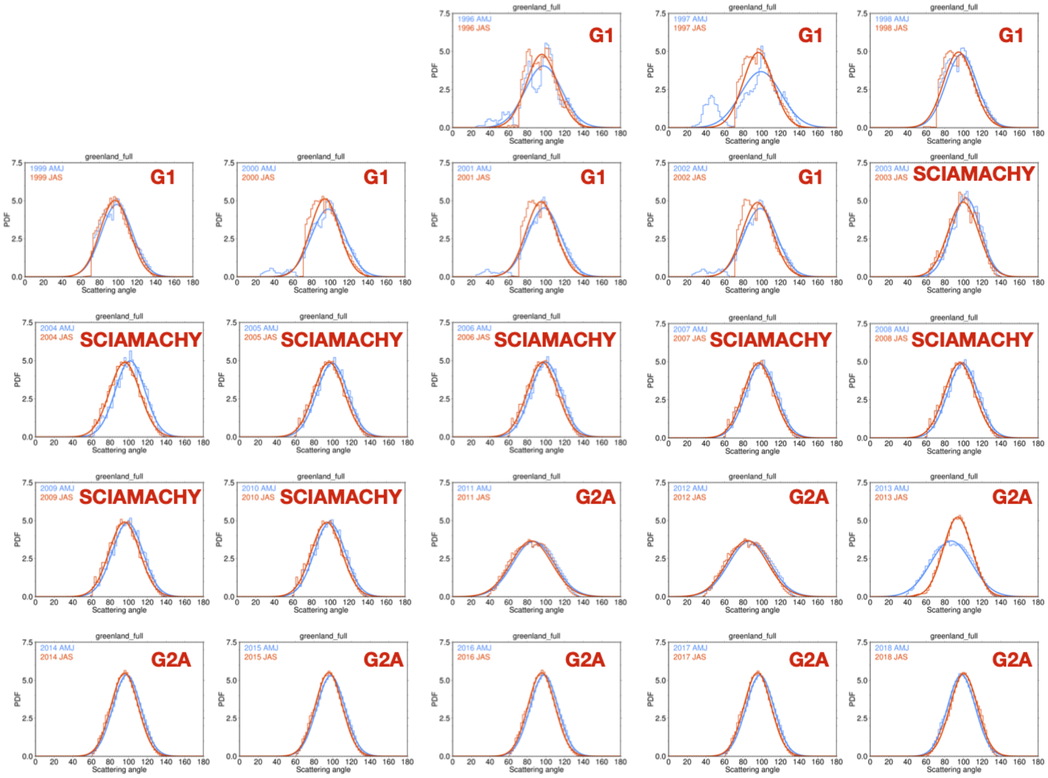

Fig. 3: Seasonal scattering angle distributions over Greenland for each year from 1996 to 2017.

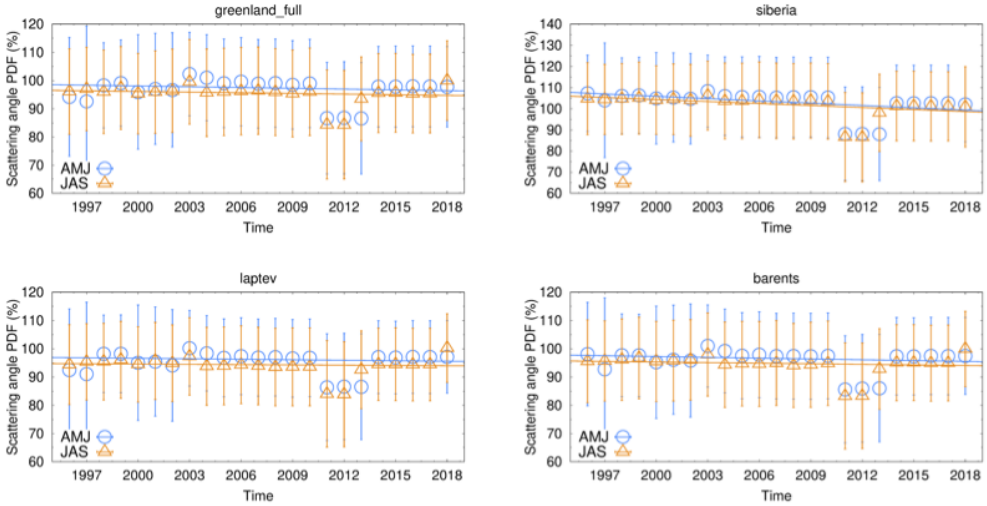

Fig. 4: The same quantities shown in Fig. 3 are plotted with 2 σ and the linear trends. See Appendix A in the manuscript for the assessment of the shift in scattering angle.

R21

Figure 3: There is a marked change in the standard deviation between the GOME and SCHIAMACHY data sets. This needs to be explained. And of great importance to this paper, the implications of this change on the ability to detect trends must be discussed.

A21

We will discuss it with the aid of the following text.

Please note that at line 434, Appendix A, the reader finds the following sentence: "Monthly aggregation leads to higher means for finer spatially-resolved instruments than otherwise".

The sentence indicates what the data say: GOME has a footprint of 320 × 40 km^2, considerably coarser than the follow-on sensors SCIAMACHY (60×40 km^2) and GOME-2 (80×40 km^2). This leads to different mean reflectances and standard deviations between sensors because the integration time of the acquiring on-board electronics for a coarser pixel is longer than for a finer pixel. This averages out sub-pixel heterogeneity of the sensed scene differently.

We account for this effect by assessing trends in reflectances not from mean values $Y(t, i)$ but from anomalies (see Eq. B1 in the manuscript) instead. The anomalies are customarily normalized with the standard deviation of the reflectances $s(t, i)$.
The standardized anomalies $y(t, i)$ are defined as

$$y(t,i) = \frac{Y(t,i) - \overline{Y}(t,i)}{s(t,i)}. \tag{1}$$

where $\overline{Y}(t, i)$ is the climatological mean of reflectance at time t and location i.

This is a common technique for the analysis of records which might be heterogenous in scale as in our case (see Section 3.4.3, pages 50-51 in Wilks, 2019).
Please note that normalization to the standard deviation of a sample is a linear transformation. Therefore, the underlying shape of the sample distribution is untouched and any non-Gaussian data sample is not made any more Gaussian. In other words, our approach does not precondition the sample statistics, hence the assessment of the trends' confidence intervals and the significance are not corrupted either in any way. Moreover, the bootstrap resampling technique has been chosen advisedly to avoid any ad-hoc assumption (i.e. parameterization) on the distribution of the sample.

In essence, each step of our data harmonization is similar to the ones carried out in Beirle et al. (2018), who deal with the same sensors and basic physical quantities (radiances and/or reflectances).

Wilks, D.S., Statistical Methods in the Atmospheric Sciences (Fourth Edition), Elsevier, `https://doi.org/10.1016/B978-0-12-815823-4.09987-9`, 2019.

Beirle, S., Lampel, J., Wang, Y., Mies, K., Doerner, S., Grossi, M., Loyola, D., Dehn, A., Danielczok, A., Schroeder, M., and Wagner, T.: The ESA GOME-Evolution "Climate" water vapor product: a homogenized time series of H2O columns from GOME, SCIAMACHY, and GOME-2, Earth Syst. Sci.

Data, 10, 449–468, `https://doi.org/10.5194/essd-10-449-2018`, 2018.

C21

(Lines 292–298) Figure 3 shows that the standard deviation of RTOA for GOME is smaller than the other sensors. GOME has a considerably coarser pixel size than the follow-on sensors (see Tab. A2). This leads to different mean RTOA and standard deviations because the integration time of the acquiring on-board electronics for a coarser pixel is longer than for a finer pixel. This averages out sub-pixel heterogeneity differently. We account for this effect by assessing RTOA trends not from mean values but from anomalies (see App. B) instead. The anomalies are customarily normalized with the standard deviation as a common technique for the analysis of records which might be heterogenous in scale, without changing the underlying sample distribution because standardization of anomalies is a linear transformation (Wilks, 2019).

R22

Figure 3: There is a large discrepancy between SCIAMACHY and MERIS in the fall-winter. This discrepancy should be explained along with its implications for the results.

A22

This discrepancy has no implications for the results. We do not analyze fall and winter months, as stated at lines 87–90 of the introduction: "*A key set of satellite sensors record backscattered radiation in the solar portion of the spectrum. Consequently, this study focuses on the months between April and September.*

Nevertheless, please note that MERIS has a swath of 1150 km, whereas SCIAMACHY has a swath of 1000 km. This implies that with the onset of the polar night at high latitudes, the western part of the scan of both sensors (which are polar orbiters in descending node) will include increasingly dark Arctic areas, the MERIS scan being more northward leaning. Therefore, any averages of MERIS measurements will include more dark scenes than those in an average calculated from SCIAMACHY measurements. For this reason, the MERIS reflectances in fall and winter months are generally lower than those by SCIAMACHY.

What is important for our objectives is that during the months of full illumination (up to 85 °north latitude) the reflectances measured by both sensors are comparable and that there is no divergence between them over time. This is indeed the case.

We will add the above explanation to the manuscript.

C22

(Lines 279–285) The discrepancy between MERIS and SCIAMACHY in the fall and winter months, as long as sunlight is available, can be tracked to the different swath widths of the respective sensors. MERIS has a swath of 1150 km whereas SCIAMACHY has a swath of 1000 km. This implies that with the onset of the polar night at high latitudes, the western part of the scan of both sensors (which are polar orbiters in descending node) will include increasingly dark Arctic areas, the MERIS scan being more northward leaning. Therefore, any averages of MERIS measurements will include more dark scenes than those in an average calculated from SCIAMACHY measurements. For this reason, the MERIS reflectances in fall and winter months are generally lower than those by SCIAMACHY.

R23
Line 188: “small downward trend”. If I’m interpreting the numbers on Fig. 3 legend correctly, then the “trend” is actually within the 95% confidence interval of 0 (i.e., no trend). On line 190 you say that this is a “significant decrease.” By this do you mean statistically significant? And if so, that should be stated clearly.

A23
Yes, both remarks are correct. We will clarify the text accordingly.

C23
(Lines 299–300) A negligibly small and statistically insignificant downward trend of . . .

R24
Line 189: “at time t.” I assume this means at the given time of the year, so that information should be included.

A24
Yes, correct. We update the text accordingly. See also response A24 to the first referee.

R25
Line 205-206: Yes, some of those negative anomaly areas are open ocean, but some of those are also over sea ice pack, and the year-to-year variability of sea ice extent is important here. Before attempting to draw this type of conclusion, it seems imperative to use the actual sea ice extent, which is readily available, to confirm that the negative trends are indeed over open ocean as stated and/or to what degree that is true. I have the same comment for line 235 where changes are again related to regions of sea ice loss, but actual sea ice extent is not shown or discussed.

A25
We will update Figure 5 of the manuscript with Fig. 5 in this document and corresponding explanation.

C25
(Lines 308–333) To answer these questions in the following, we map RTOA in the Arctic, gridded at 1 × 1.5 degree latitude and longitude. Fig. 5 shows the spatially resolved RTOA trends for 510, 560, 620 nm over the Arctic region for AMJ and JAS. The mean seasonal sea ice extent is superimposed and colored green for year 1996 and purple for 2017. Sea ice extent is identified as those surfaces with at least local 75% sea ice concentration. Data of sea ice concentration are from Walsh et al. (2019). Similarly, Fig. 6 shows trends for the analyzed wavelengths for the 12 Arctic regions, that are defined using the geographical subdivision proposed by Serreze and Barry (2014) and Wang and Key (2005a) (see Fig. B1). Trends for AMJ are shown in green and the JAS trends for selected spectral bands are shown in blue. The red symbols show the absolute averages of the RTOA values at the beginning of the record for the respective seasons.
There are marked regional differences. Those that are statistically significant (at 95% confidence level)

are shown with red crosses. For AMJ a significant negative trend over the Barents Sea is compensated at all three wavelength bands, by a positive RTOA trend over Greenland, the Canadian Archipelago and Western Arctic Seas. In JAS, the negative trend shifts towards areas of the Kara, Laptev and Chuchki Seas. These are Arctic areas having open ocean and are experiencing significant sea ice loss during the period of study. Statistically insignificant increases in RTOA are found over the boreal land masses. However, significant increases in RTOA are observed over Greenland and parts of the Arctic Atlantic sector. In general, the trends are negative and statistically significant in both seasons where sea ice retreats, such as in AMJ for the Barents Sea (Onarheim et al., 2018) and the perennial sea ice zone around the North Pole. For the remaining areas that cannot be directly explained by the difference in sea ice extent, we assume patchy residual sea ice concentrations below 50% closer to Eurasia and occurrence of melt ponds on the sea ice pack. In both cases, open ocean areas and freshwater lower the albedo of the scene sensed by the satellites.
While areas with negative trends are spectrally neutral in both magnitude and statistical significance, areas of positive trends like the belt from the Canadian Archipelago, Beaufort and Chukchi Seas in AMJ and, to a smaller extent, Greenland in both seasons, show a increase in trend values and significance from 510 to 620 nm. While we cannot completely rule out the broadband influence of ozone trends (see App. D) on reflectances, the spectral patterns are coherent with an increase in some cloud properties conducive to snowfall and a brighter surface. Despite its proximity to the Canadian Archipelago, Baffin Bay has changes in RTOA trends that would more closely match the Eastern Arctic Seas region. Over the Hudson Bay, the RTOA trends show unusual patterns. They are largely positive in JAS and relatively strongly negative in AMJ.

Walsh, J. E., W. L. Chapman, F. Fetterer, and J. S. Stewart. 2019. Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 2. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: `https://doi.org/10.7265/jj4s-tq79` [last accessed: June 2021].

R26

Line 208: Can you explain the Greenland trend?

A26

In this section we describe only the mere results of reflectance. We defer the explanation to later sections when also cloud properties and radiative forcing are presented. It is an editorial choice.

R27

Line 209-210: The text appears to be backwards. There is a strong negative trend in the Barents Sea in AMJ and a positive trend in JAS. And how is this similarly extraordinary to what was observed over Greenland?

A27

We will swap the sentence. Our attention has been caught by the behaviour of reflectance trends and cloud properties in the Barents Sea. Namely the strong significant negative reflectance trends in AMJ and the ensuing build-up of reflectance, correlated with the increase of CFC and COT liquid in JAS.

C27

We remove the word “extraordinary”.

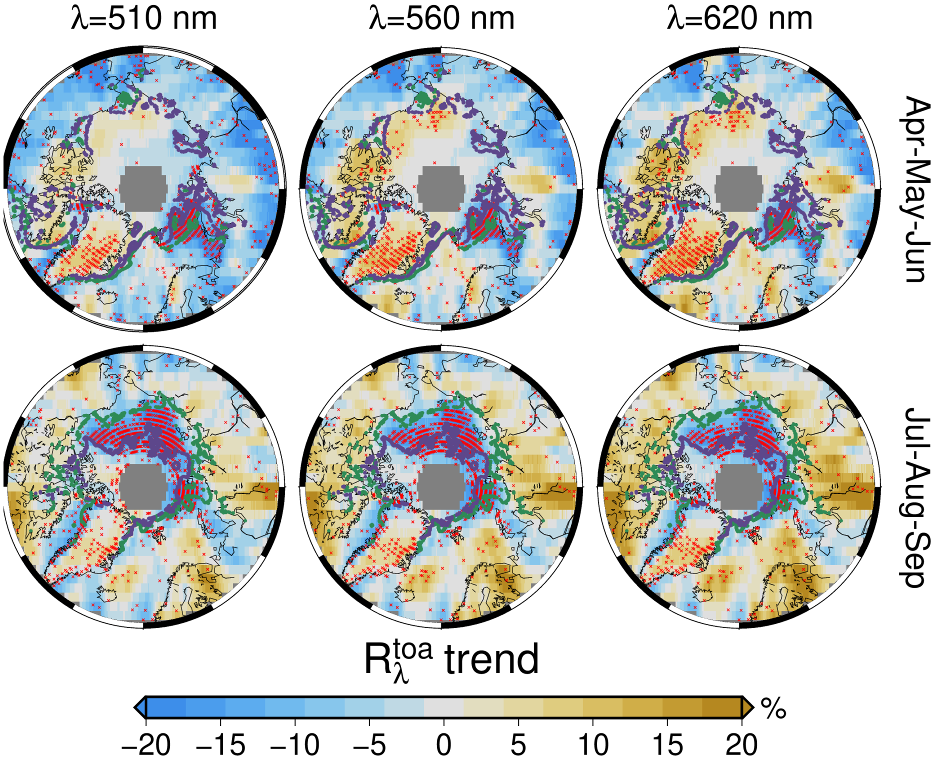

Fig. 5: Seasonal RTOA trends for 1996-2018 at selected λ for Arctic spring (AMJ, top) and summer (JAS, bottom). The values are relative to the first season of the record. Sea ice extent for 1996 in green and 2017 in purple. Stippling in red indicates significant trends at 95% confidence.

R28

Line 215-216: This statement that the JAS trends at 760 nm are large: First, is this specifically in reference to Hudson Bay or to all regions? And regardless of that, it is not clear from Fig. 6 that 760 shows particularly large trends relative to any other wavelength. What is the point of this statement? Perhaps this was intended to be part of the next paragraph, which appears to focus more on 760 nm?

A28

Yes, indeed we can group this sentence together with the next paragraph. The reason for this statement is that 760 nm is the only channel with a very strong gaseous absorption and is not in the broadband continuum like all other channels. 760 nm bears more information on light scattering aloft than at the surface, because of the strong columnar absorption of atmospheric oxygen largely extinguishing photons before they impinge on the ground. No other Arctic region shows a similar behaviour except, to a lesser extent, Barents Sea.

C28

(Lines 334–344) Although not of the same magnitude, almost all regions show a reflectance change at 760 nm. This wavelength is the only channel with a very strong gaseous absorption and is not in the broadband continuum like all other channels. 760 nm bears more information on light scattering aloft than at the surface, because of the strong columnar absorption of atmospheric oxygen largely extinguishing photons before they impinge on the ground. Oxygen absorption is modulated primarily by CTH and, to a lesser extent, by CFC and optical properties such as CA and τ. In this context, where a positive trend value of RTOA at 760 nm is observed, greater than the other channels, we deduce a clear change in occurrence of clouds or one of their physical or scattering properties. This is the case for Greenland during AMJ and JAS, for the Canadian Archipelago and the Barents, Chuckchi, East Siberian Seas only in AMJ, for the Barents Sea the Hudson Bay, the Atlantic corridor and the Siberian continent only in JAS. Knowing that RTOA is influenced by scattering and absorption in the atmosphere (Sledd and L'Ecuyer, 2019; Donohoe and Battisti, 2011) and that the atmospheric RTOA can be additionally partitioned into cloud, aerosol and gas contributions, this prompted us to examine changes in those cloud properties which directly influence the spectral RTOA trends.

R29

Line 230-233, and Fig. 7 caption: What are warm liquid clouds and cold ice clouds? Are there cold liquid clouds (i.e., mixed-phase clouds)? Or do you simply mean liquid vs. ice clouds? If the later, then the "cold" and "warm" should be deleted. Otherwise, further explanation is needed.

A29

We used the terminology to additionally characterise clouds as function of temperature (i.e. altitude), implying that clouds at higher temperatures should be lower placed than the cold clouds. However, we are aware that this general picture is not accurate for the Arctic, let alone the occurrence of inversion layers which may decouple the surface from the lower troposphere.

C29

We remove "warm" and "cold".

R30

Line 230-233. Also, it is not clear if the phase of clouds is shifting (i.e., more liquid clouds and less ice clouds, but the total CFC stays the same) or if there is the same amount of liquid and ice clouds but the actual COT of those clouds is changing. In other words, are these COT trends due to changes in cloud phase partitioning or the actual COT of clouds of a given phase when they exist? The statement made in lines 258-259 seems to suggest that the changes are due to occurrence fraction of liquid vs. ice.

A30

Indeed, the comment is correct. Since no significant changes in cloudiness are detected at the pan-Arctic level (see Fig. 7 in the manuscript, topmost time series of CFC), we conclude that, as the cover fractional cover is unchanged within error, the optical thickness of clouds is changing as a result of changes in the amounts of liquid and ice particles in the cloud. Evidence for an increasing amount of liquid water cloud in the Arctic (and Antarctic) is provided in Fig. 6, which shows seasonal latitudinal changes of the fraction of liquid clouds in the time frame of our study.
We add a sentence explaining Fig. 6.

R31

Line 248-249: Fig. 7 and Fig. 8 do not show a positive trend in CTH over Greenland or Hudson Bay in JAS.

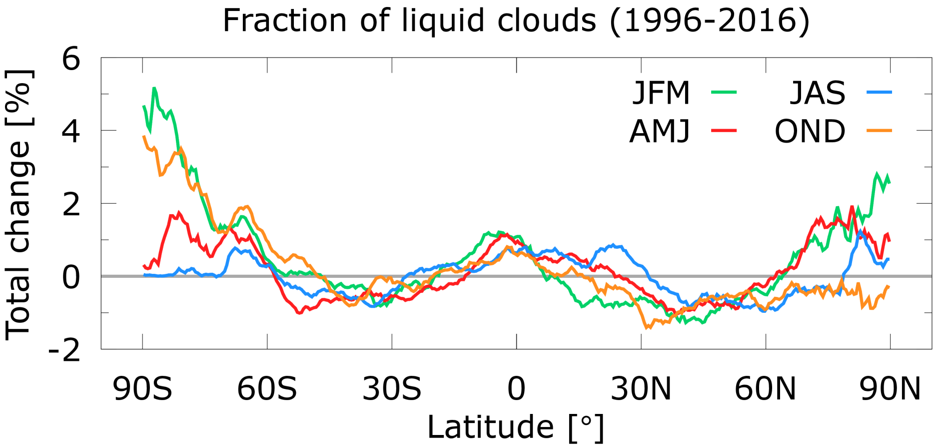

Fig. 6: Seasonal total change of fraction of clouds in the liquid phase.

A31

Yes, correct. We will change the text accordingly.

R32

Line 252: I believe you mean Baffin Bay instead of Hudson Bay.

A32

Yes, correct. We update the text accordingly.

R33

Line 255-256: I do not understand how this sentence starting with "Conversely" is actual converse to the prior sentence, which discusses opposing trends of liquid COT and ice COT. This sentence discusses the fact that liquid COT increases in both AMJ and JAS.

A33

We agree that the sentence can be improved. We intend to explain that in some regions the increase in liquid COT does not necessarily result from a decrease in ice COT and vice versa.

R34

Figure 7: Make the colorbars the same for the liquid and ice COT fields so they can be readily intercompared.

A34

The colorbar has been updated. Please, note that we will add the panel of τ-total from Fig. 12 to this figure.

R35

Line 256-258: Do you mean "nearly unchanged" (which would be a trend of 0) or do you mean that

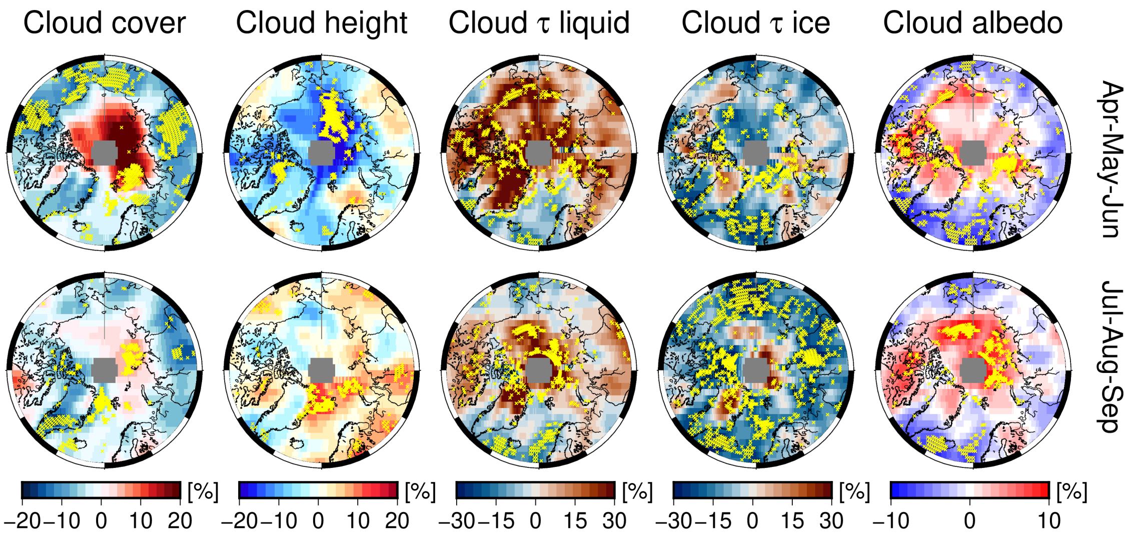

Fig. 7: Figure 7 of the manuscript with the updated color bar for τ-ice.

the trends remain similar for the different seasons?

A35

We mean that the trends are similar in the different seasons. We will clarify this in the text.

R36

Line 261-262: What does "for which a marked change of the spatial rather than temporal scale is observed" mean? The spatial distribution of changes is very similar to liquid COT and to some degree CFC. As for temporal scales.... The trends themselves (which are the temporal scale) are relatively large. Or do you mean temporal scale as in comparing the two seasons? In which case there is little difference between the seasons. This statement, and many others, are simply not clear.

A36

We intend to explain that the trends in CA do not appreciably change between seasons (temporal change) but have changes in their geographical (spatial) features. CA largely follows liquid COT values as a result of the well known relationship between the two cloud properties. However, CA over land masses at lower latitudes shows a different behaviour to that of liquid COT.

See also response A33 to the first referee. We will improve the sentence as follows.

C36

(Lines 384–385) The polar plots of seasonal trends in cloud albedo (CA) in Fig. 8 show that the magnitude of the positive trends in JAS is larger than those of AMJ but the spatial extent of the CA trend values are similar in both seasons.

R37

Line 278-280: There are multiple ways to compute CRF and these are not consistent with each other.

For example, some people use radiative transfer algorithms to compute the equivalent clear sky radiative fluxes by removing the cloud, but not modifying the other features like moisture or temperature that are associated with the cloudy air mass. Others will simply compare observed cloudy and clear states to get the radiative difference between these. There are a number of other considerations, such as the change of surface albedo under cloudy vs. clear skies, which could impact the results depending upon how this is accounted for. At a minimum this manuscript needs to clearly state how the CRF was derived so the results presented here can be realistically put into context of the past work on CRF done across the Arctic. Moreover, it is essential to understand how CRF was calculated so it is possible to interpret the CRF results (i.e., how much does the actual change in surface albedo due to decreased sea ice extent translate into enhanced effective cloud cooling?)

A37

We will add the definition of CRF here below. The additional considerations about its dependency on surface albedo have been added in the section 2.2 of the manuscript (see C15).

We repeat here the most important details. The instantaneous fluxes, at the basis of the monthly averages used in our study, have been computed with the approach by Henderson et al. (2013). Surface albedo at visible and near-infrared wavelengths are based on spatio-temporally resolved MODIS climatologies, which are used in the cloud retrieval algorithm. Sea ice extent is taken from measurement in the microwave.

During the preparation of the manuscript, we have generated also the results shown in Figures 8 and 9. Figure 8 shows histograms of SWE and LW CRF, for the different underlying surface type: all Arctic, sea ice covered areas (sic), marginal sea ice zone (msz), and open waters (oce) for the two periods 1982–1991 and 2005–2014. The first period is prior to the observation of Arctic Amplification and the second period covers the current Arctic Amplification. Sea ice areas have values of SW CRF can be larger than the LW CRF, leading to a positive CRF. With decreasing sea ice extent, SW CRF exceeds LW CRF, leading to a negative net CRF. The same data are plotted in the left column of Fig. 9 for a continuous SIC value range.
The right panels in Figure 9 show that the the (negative) SW CRF trend increases for a decreasing sea ice extent, while the LW CRF trends slightly increase. Inspecting qualitatively the crossing point between trends in SW and LW CRF as function of SIC, we see that already for SIC change of 0.05% month^{-1} suffices for the SW CRF to offset the LW CRF. In these results the CRF changes as a function of cloud property are combined.

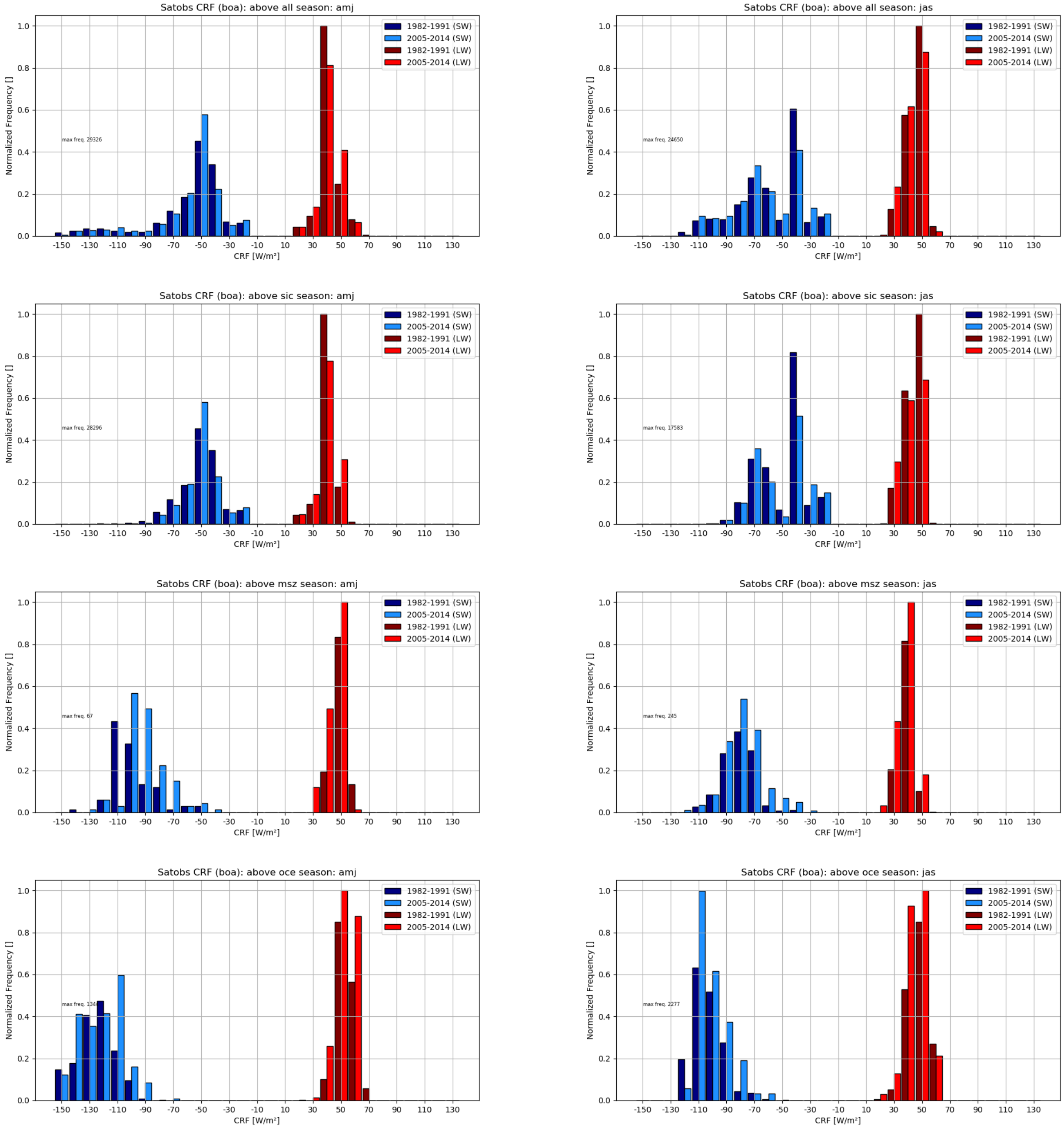

Fig. 8: The seasonal (left column AMJ, right column JAS) SW and LW CRF-components of cloud radiative forcing above all Arctic surfaces (top row), above sea ice covered areas (second row, "sic"), marginal sea ice zone (third row, "msz") and open waters (bottom row, "oce"). The CRF-SW is plotted in blue and the CRF-LW is plotted in red (for two different periods we use different shades of blue and red, respectively). Note that each individual distribution has been normalized to the value of highest occurrence given in each plot as "max freq". Data of sea ice concentration are from Walsh et al. (2019).

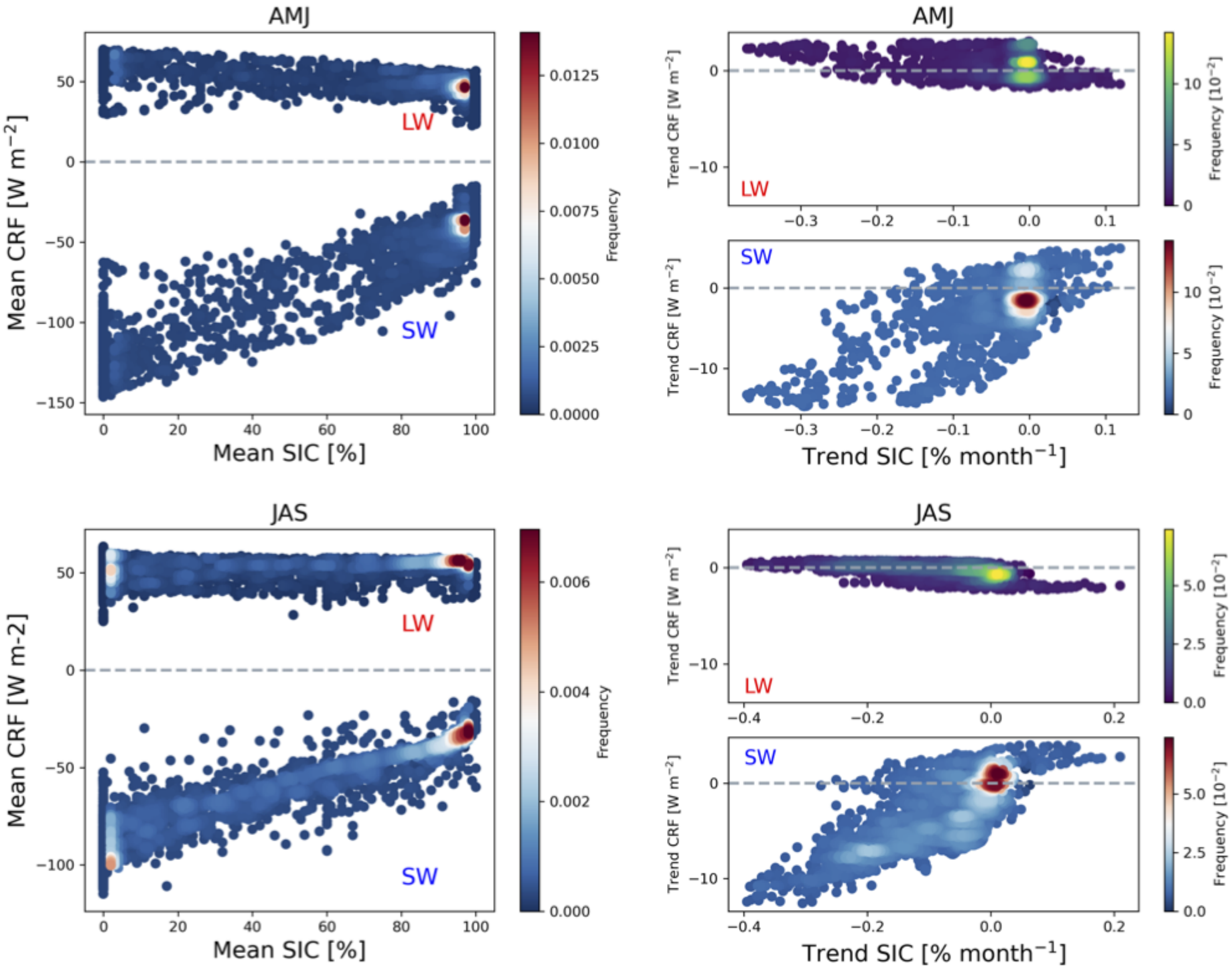

Fig. 9: Distribution of mean SW and LW CRF (W m^{-2}) as function of SIC (left panels). Change in SW and LW CRF as function of SIC trends (right panels). The top row is Arctic spring (AMJ), bottom row is Arctic summer (JAS).

Walsh, J. E., W. L. Chapman, F. Fetterer, and J. S. Stewart. 2019. Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 2. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: `https://doi.org/10.7265/jj4s-tq79` [last accessed: June 2021].

C37

(Lines 401–404) We compute CRF at the bottom-of-atmosphere (BOA, at the surface) from the differences between the downward and upward fluxes of SW and LW for all-sky and clear-sky conditions as follows

$$\mathrm{CRF}^{\mathrm{boa}} = (\mathrm{SW}_{dn} - \mathrm{SW}_{up} + \mathrm{LW}_{dn} - \mathrm{LW}_{up})^{\mathrm{boa}}_{\text{all-sky}} \tag{2}$$

$$- (\mathrm{SW}_{dn} - \mathrm{SW}_{up} + \mathrm{LW}_{dn} - \mathrm{LW}_{up})^{\mathrm{boa}}_{\text{clear-sky}} \tag{3}$$

R38

Line 285-286: The language is not precise here. The SW values quoted are not for cloud reflection, but for the difference in SW CRF. Similarly, clouds do not emit 36 or 43 W/m2, but rather this is the LW CRF.

A38

Thank your for pointing this out. We shall improve the text accordingly.

C38

(Lines 409–411) For instance, total CRF over Greenland is +14.9 and +23.5 $\mathrm{W\,m^{-2}}$, which corresponds to the Arctic sectors over which the difference in SW CRF is the smallest (-19.8 in AMJ and -21.3 $\mathrm{W\,m^{-2}}$ in JAS) while LW CRF amounts to 36.2 in AMJ and 43.3 $\mathrm{W\,m^{-2}}$ in JAS.

R39

Line 288-292: First, it would be better to put the explanation for Greenland right after the Greenland result and the Atlantic sector explanation after the Atlantic sector results so as not to confuse the reader by jumping back and forth. Second, there are some basic mis- interpretations here. With regard to the statement "darker surfaces of the Atlantic corridor and Baffin Bay emit LW more effectively": "darker surfaces" is typically referring to the amount of reflection, and thus impacts SW; the "darkness" of the surface does not directly impact the LW emission, rather that is the temperature, which happens to be higher over ocean that over sea ice but has nothing to do with the darkness of the surface. Additionally, the reason that SW outweighs LW in the Greenland Sea / Baffin Bay is not predominantly related to the liquid COT but rather to the surface albedo; at the relevant latitudes and a surface albedo less than 0.1, almost any cloud will result in SW outweighing LW effects (e.g., Shupe and Intrieri Fig. 7). On the other hand, over higher albedo surfaces like sea ice (albedo $>$ 0.6) the dominance of SW vs LW effects is much more sensitive to the cloud COT.

A39

We thank the referee for pointing these issues out. The referee is correct that darker implies a change in the SW CRF component and is not suitable for the use with the LW CRF component. Indeed, our description of the dependence on the surface brightness did not mention temperature as driving factor of LW emission. We implicitly assumed it could have been inferred by the reader. We explain it better and clarify the issues raised in our text.

C39

(Lines 411–419) The combined effect of the brighter surface and comparatively low optical τ (irrespective of the phase) over Greenland (8.4±7.3 in AMJ and 6.7±3.5 in JAS) increases SW reflectivity and damps upwelling LW. The minimum total CRF is measured over the Baffin Bay, the Atlantic corridor and Barents Sea in AMJ (-51.1 $\mathrm{W\,m^{-2}}$) and JAS (-43.4 $\mathrm{W\,m^{-2}}$). For the same seasons, darker surfaces of the Atlantic corridor and Baffin Bay imply the presence of open water masses, which have higher temperatures and, therefore, emit LW more effectively. However, SW offsets LW and total CRF turns negative owing to larger τ-liquid over the Greenland Sea (14.5±3.4 in AMJ and 15.6±3.3 in JAS) or the Baffin Bay (14.6±5.3 in AMJ and 13.4±3.0 in JAS). At low surface albedos, typically less than 0.1 (Fig. 7 Shupe and Intrieri, 2004), and for the majority of clouds SW CRF outweighs LW CRF, whereas

SW radiative effects offset those by LW over higher surface albedos (> 0.6), making CRF more sensitive to changes in cloud τ.

R40
Line 293-294: Fig. D1 does not show climatological annual pan-Arctic total CRF, but rather shows trends in various CRF terms. Where do these numbers in the text come from? It would be very useful to include polar projection plots of the annual LW, SW, and total CRF to aid in the discussion around this part of the text.

A40
We agree with the referee. The numbers in the text had been computed without showing the maps of climatological annual and seasonal CRF and its components. We add the panels of Fig. 10 to the Appendix with the corresponding maps as companion of Figure D1. The figure is attached here below.

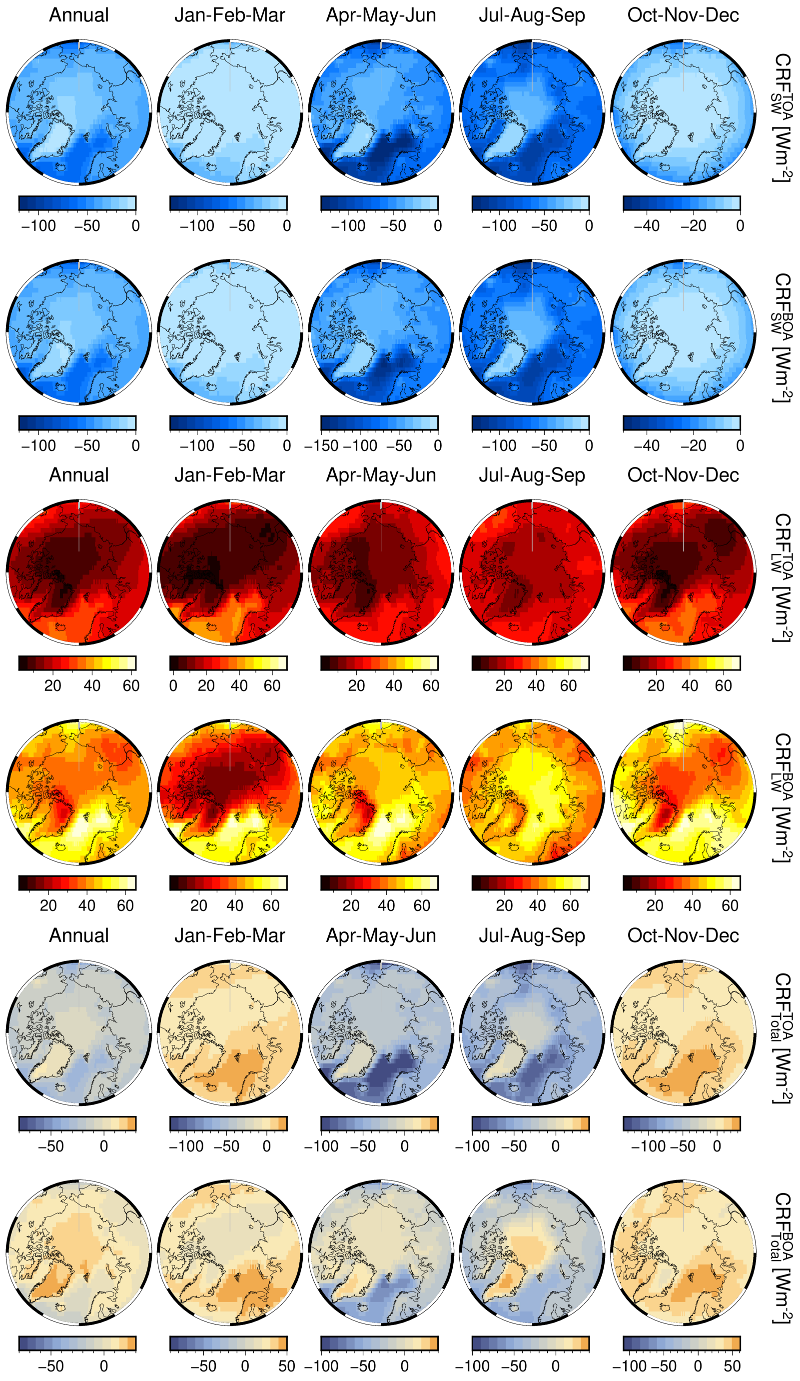

Fig. 10: From left to right, annual and seasonal average values of SW (rows 1-2), LW (3-4) and total (5-6) cloud radiative forcing (CRF, W m^{-2}) at TOA and BOA, respectively. Note the different color scales to match the CRF ranges.

R41

Line 296-298: "Consequently, the Arctic surface is warmed by clouds throughout...." It is not clear what this statement is referring to. Presumably this is referring to the annual total CRF (which is not shown anywhere).

A41

Yes, correct. We have added Fig. 10 to the Appendix.

R42

Line 304-312: These results are entirely consistent with the change in surface albedo. i.e., there is little change in the surface albedo over land surfaces, Greenland, and the N. Atlantic because there is no major shift in surface properties there. On the other hand, over the Barents/Kara in spring and over the whole Arctic Ocean domain in summer the declines in sea ice have led to a decrease in surface albedo. This leads to a larger negative SW CRF (independent of cloud changes), which increasingly outweighs the LW CRF.

A42 The comment is correct. See also A37. We update the text accordingly.

C42

(Lines 440–443) The influence of changes in surface albedo is manifested in these results. Where surface albedo remains almost constant (land masses, Greenland, and the Atlantic corridor) then CRF trends are of lesser magnitude. Instead, where the surface experiences more substantial changes, both seasonally and over the long term, trends in CRF are amplified, due to a greater influence of SW over LW.

R43

Line 316: I don't know what "wetter Arctic clouds" means. In general, "wet" means water in any of its phases. But this paper has not established if there is in fact more water mass (LWP+IWP) in clouds. Rather, what has been show is that often the changes offset each other, and the percentage change (Fig. 8) is often larger on the IWP decrease than on the LWP increase. Nonetheless, the information has not been provided here to demonstrate if there is in fact more condensed mass in clouds or not (although it could and should be). Additionally, the paper has shown some changes in the COT of liquid vs ice clouds, but this is not changing how wet the clouds are but rather how optically thick they are. Lastly, it has not been demonstrated here that anything has actually changed with the amount of cloud or the condensed mass of the cloud. The changes in liquid vs ice could simply be a shifting from ice towards liquid (i.e., same mass), which would be expected as atmospheric temperatures slowly warm. The paper needs further work to disentangle these key points and to draw the appropriate conclusions as to what is actually changing. For this specific statement highlighted here, if anything, the conclusion would rather be "....compensated for by more reflective Arctic clouds" (although to truly make that statement would require spatial maps and temporal trends for total COT).

A43

By "wetter" we mean to express that the amount of liquid water in the clouds has increased. We will replace "wetter" with "more liquid" where appropriate, starting with the title. We will also add the new figures to the manuscript.

We provide results that answer the two questions posed by the referee: **Q(1)** has the total mass of condensed water in clouds increased? **Q(2)** How does the total optical thickness of clouds change?

A(1) Figure 11 shows seasonal total change (in %) from the first season in the record of LWP, IWP and cloud water path (LWP + IWP). Indeed, the loss of IWP is larger than the increase in LWP. The seasonal correlation between CWP and its water/ice component is respectively 0.79 / 0.75 in AMJ and 0.57 / 0.84 in JAS.

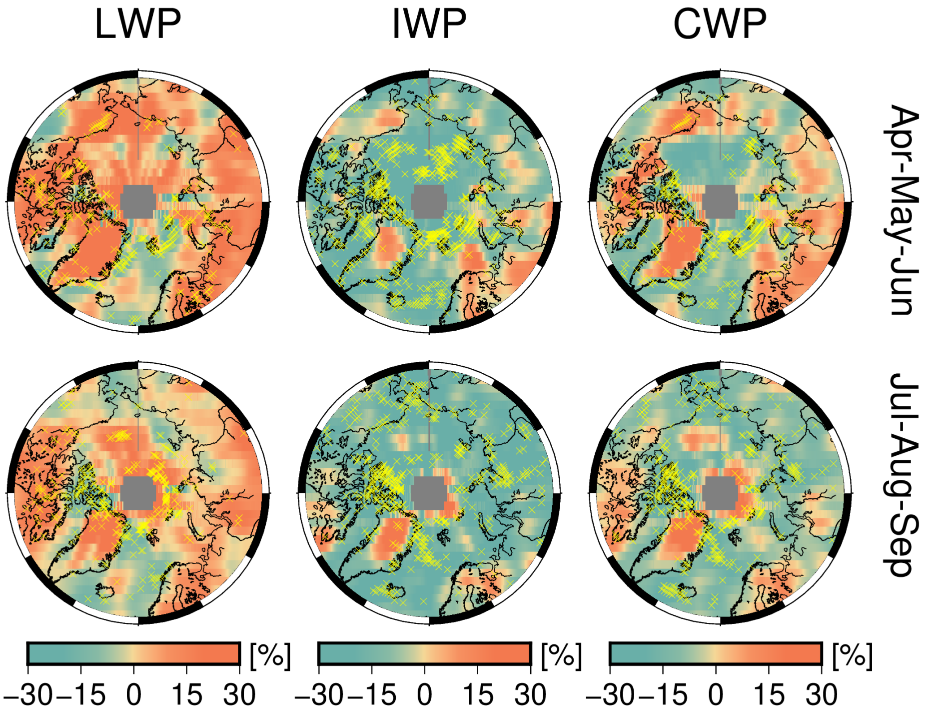

Fig. 11: Seasonal trends of LWP, IWP and CWP.

A(2) From Figure 12, total COT has remained approximately unchanged throughout the record. The seasonal maps reveal that trends in total COT are more correlated with trends in liquid COT than with those in ice COT. The seasonal correlation between total COT and liquid/ice is respectively 0.84 / 0.21 in AMJ and 0.63 / 0.50 in JAS.

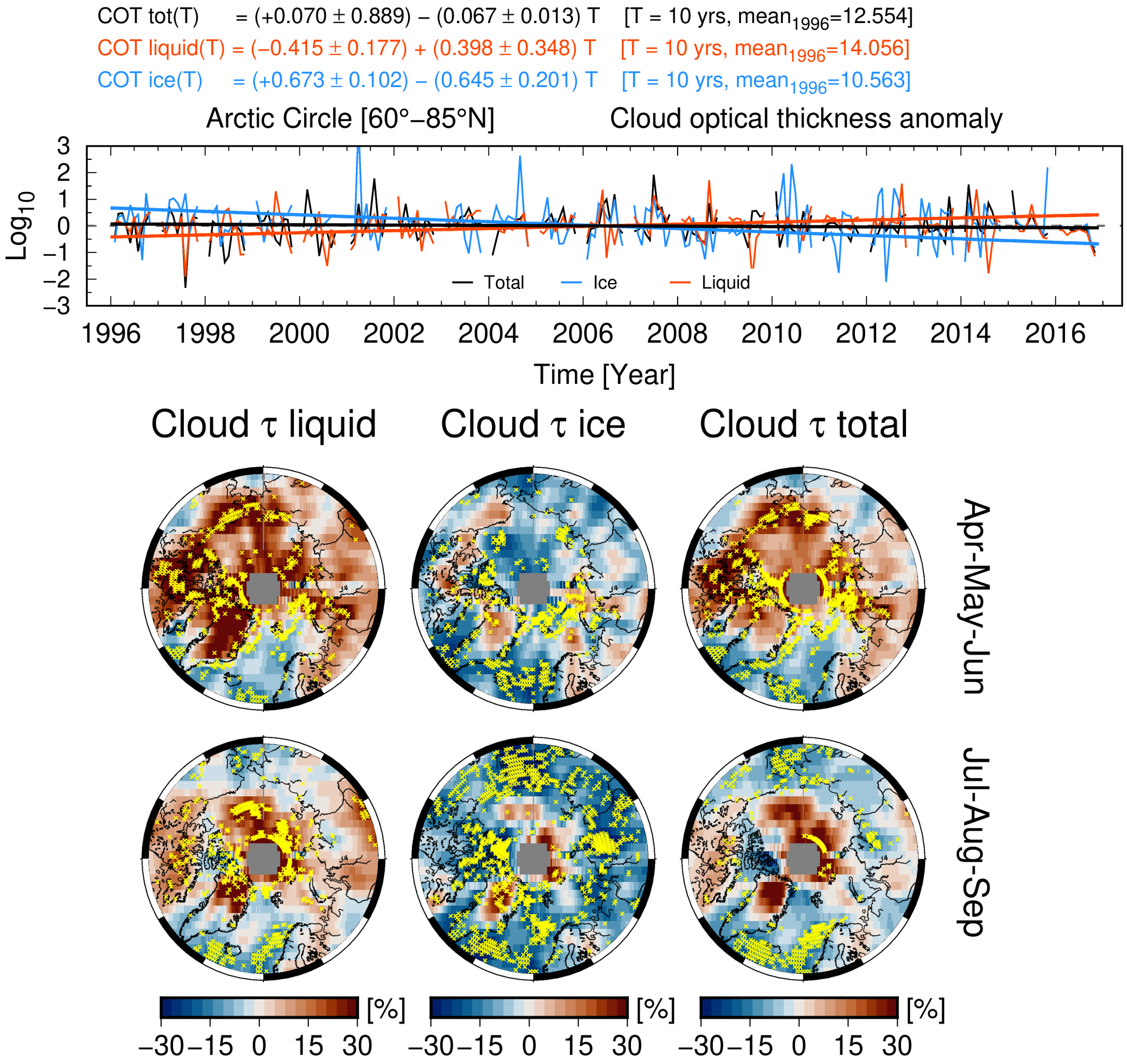

Fig. 12: Top: time series and trends of optical thickness for liquid, ice and all clouds. Bottom: seasonal trends.

The values of total change within the record, underlying Figures 11 and 12, are reported in Table 1.

Table 1: Seasonal pan-Arctic total change ± one σ (%) from the first season in the record of physical and optical properties of clouds for all clouds and the liquid and ice phase. CWP and τ total values are weighted by the relative occurrence of liquid/ice clouds in AMJ (0.54/0.46%) and in JAS (0.63/0.37%).

Parameter	AMJ	JAS
LWP	$+11.58 \pm 3.10$	$+4.57 \pm 6.64$
IWP	-14.54 ± 23.50	-16.47 ± 20.47
CWP	-0.51 ± 11.01	-3.13 ± 8.59
τ liquid	$+12.46 \pm 5.43$	$+3.95 \pm 2.82$
τ ice	-7.12 ± 12.25	-12.67 ± 15.41
τ total	$+3.40 \pm 6.14$	-3.66 ± 7.29

We conclude that while the total mass of condensed water in both phases (i.e. liquid plus solid) has not considerably changed in AMJ and has moderately decreased in JAS. This is due to a faster loss of ice which is not compensated for by an increase of liquid water in the same amount. This implies a decrease of τ ice, for the concurrent increase in τ liquid, and the decrease of ice water path for the concurrent increase of liquid water path.

C43

(Lines 446–459) We attribute the reason for this decreasing trend to be a decrease in sea ice, compensated for by more liquid Arctic clouds. This results from their increasing liquid water content and a concurrent simultaneous decreasing ice content. Therefore, the thermodynamic phase separation of clouds is not only optical (Fig. 7) but also physical, considering Fig. 11. Indeed, the loss of IWP is larger than the increase in LWP. The cloud water path (CWP) is defined as the weighted sum of the two phases, whose relative occurrence is 0.54/0.46% in AMJ and 0.63/0.37% in JAS, for the liquid/ice clouds respectively. The seasonal correlation between CWP and its liquid/ice component is respectively 0.79/0.75 in AMJ and 0.57/0.84 in JAS, showing that the loss in ice water content is the main driver for the loss of total water condensate in clouds, more in summer than in spring. While highly variable at pan-Arctic scale, the total change in CWP amounts to -0.51 ± 11.01% in AMJ and -3.66 ± 7.29 % in JAS. Notably, the majority of water path changes exceeding natural variability are those of LWP/IWP decrease over areas of sea ice melting and only partly of LWP increase over land masses, Canadian Archipelago, some spots over Greenland and the Beaufort Sea in JAS. In light of the results presented so far regarding the optical thickness and separation of the two cloud phases, it is reasonable to assume that this trend will continue in the future, allowing more patterns of statistical significance to emerge even where they have not been detected with 20 years of data.

R44

Line 328: Figures 6,7,8 do not demonstrate a moistening of clouds. If anything, they might demonstrate an increase in COT, but even that is not clear in the aggregate.

A44

With the results provided in the answer A43, we think that the increase of the liquid component of clouds is unambiguously identified in its optical and physical realization. The total optical thickness of clouds has not changed in the time considered.

R45

Line 326-327 vs Line 330-331 vs. Line 338-340. In the first sentence, it is stated that the CFC trend over Greenland turns "strongly negative" after 1995, explaining Hofer et al. But then a few sentences later it is stated that over Greenland there is an "insignificant CFC trend." Then in the third set of lines, it again mentions the Hofer et al. work and the decreasing CFC leading to more insolation. So which is it? If there is a decreasing CFC (ala Hofer et al) then there would be less clouds and more of the Greenland Ice Sheet contributing to reflected irradiance. Assuming the surface is slightly more reflective than the clouds, this would explain the total change in TOA reflectance observed in this dataset.

A45

The sentence at lines 330-331 ("insignificant CFC trend") refers to the pan-Arctic CFC trends and not to Greenland. We acknowledge that having created Figure 7 for a pan-Arctic time series and seasonal maps makes the interpretation of the text difficult, when discussing specific Arctic regions, such as Greenland in this case. Our intention is to highlight that Greenland's reflectance trends are not fully explained by CFC changes. Consequently, we agree with the referee that the reduction in cloudiness over Greenland (confirming the results by Hofer et al.) contributed to higher surface exposure and, therefore, to a positive reflectance trend over the continent.

We will clarify this in the revised text.

C45

(Lines 471–476) Greenland has a unique behavior: RTOA trends at all wavelengths are positive, irrespective of the season (Fig. 6). The AMJ RTOA trends, up to 5%, are even larger than those for JAS. This result is particularly surprising, given the insignificant CFC trend at pan-Arctic scale and the local negative CFC trend in both seasons (Fig. 8,9), thus not contributing to an increase of the overall reflectance. Therefore, we conclude that the increase in RTOA is due to the enhanced exposure of reflective surface in the southern part of Greenland, while a similar increase in the northern part is due to the simultaneous increase of $\tau-$total (Fig. 8) and CWP (Fig. 11).

R46

Line 335: Again, unless there is evidence showing wetter clouds, all you have shown is that they might be more reflective.

A46

We have provided evidence in A43 that the Arctic clouds are changing from the solid to the liquid phase, both in the optical and the physical domain.

R47

Line 345: It depends on how cloud forcing is defined, but it generally also depends on the solar zenith angle and the surface albedo.

A47
We agree with the referee regarding the instantaneous fluxes. That said, we consider that the SW fluxes in the dataset we analysed have been corrected for the low-sampling rate of a single-polar orbiter as well as for their angular dependence of the solar illumination. This is achieved by computing the diurnal cycle of solar zenith angle, by adjusting the surface albedo and, eventually, the atmospheric path lengths. The LW fluxes have been also corrected for with a cosine function derived by measurements of the geostationary SEVIRI sensor. The final average is a good approximation of a true 24h average, needed to determine the true climatological mean of fluxes. Consequently, also the average in seasons (i.e. AMJ and JAS) does not contain variations in solar zenith angle and directionality of surface reflection.

These concepts have been embedded in C15.

We point the referee to the relevant documentation.

Stengel, M., Stapelberg, S., Sus, O., Finkensieper, S., Wuerzler, B., Philipp, D., Hollmann, R., Poulsen, C., Christensen, M., and McGarragh, G.: Cloud_cci Advanced Very High Resolution Radiometer post meridiem (AVHRR-PM) dataset version 3: 35-year climatology of global cloud and radiation properties, Earth System Science Data, 12, 41–60, https://doi.org/10.5194/essd-12-41-2020, 2020.

ESA cloud cci - Algorithm Theoretical Basis Document (ATBD) of the Community Code for CLimate (CC4CL) Broadband Radiative Flux Retrieval (CC4CL-TOAFLUX) - REF: CC4CL-TOAFLUX ISSUE: 1.1 DATE: 14/10/2019. https://climate.esa.int/media/documents/Cloud_Algorithm-Theoretical-
v1.1.pdf

Shupe, M. D. and Intrieri, J. M.: Cloud radiative forcing of the Arctic surface: The influence of cloud properties, surface albedo, and solar zenith angle, Journal of Climate, 17, 616–628, https://doi.org/10.1175/1520-0442(2004)017<0616:CRFOTA>2.0.CO;2, 2004.

R48
Line 346: Here and elsewhere, including on the legend of Fig. 10, use liquid instead of water. Water can be liquid, ice, or vapor.

A48
Agreed. We replace it accordingly.

R49
Line 348-349: First, SW CRF dominates over LW CRF only for certain locations with sun high in the sky and surface albedo low. Second, how is the conclusion about CFC modulating mainly LW determined? In looking at the right half of Fig. 10, there is a general distinction for both LW and SW trends based on CFC (i.e., open vs. filled circles cluster on opposite sides of the panels).

A49
With the previous answer in mind about how the fluxes were calculated (A47), we believe that the inference in the sentence ("SW CRF dominates over LW CRF") is essentially valid, in spite of the diurnal and seasonal variation in the solar zenith angle.

From the second column of Figure 10 in the manuscript, we note that in SW there is no robust correspondence between trend magnitudes in CRF and CFC.

For LW, a linear relationship holds both between the diameter and type (filled or open) of the circles and the sign of the LW trends:

1. The circle diameter is consistently proportional to the trend magnitude in CRF_LW (i.e. greater circles correspond to larger trends in ±CRF_LW)
2. Filled/open circles (i.e. increase/decrease in cloudiness) correspond to positive/negative CRF_LW trends.

For SW, the conditions of bullets 1 and 2 are not satisfied.

We substantiate it with Figure 13. They are the analogue of Fig. 10 in the manuscript, but now CRF_SW and CRF_LW are related with CFC and not COT-liquid anymore. For the shortwave part of CRF, the seasonal coefficients of determination R^2 by CFC is comparable to those of Fig. 10 (top right) in the manuscript, which show R^2 by COT-liquid. For the longwave part of CRF, R^2 by CFC is higher than R^2 by COT-liquid (CFC: AMJ 0.98 for both above ocean and all areas; JAS 0.87 above ocean 0.94 above all areas. COT-liquid: AMJ 0.39 / 0.02 above ocean / all areas; JAS 0.65 / 0.19 above ocean / all areas). We conclude that CFC modulates LW more than SW.
The accompanying text explaining Fig. 13 will be added to the revised manuscript.

C49

(Lines 500–512) Cloud forcing at the surface depends on cloud property changes. The behavior is summarized in the seasonal and regional charts of Fig. 12, in which mean value and trend of SW, LW and total CRF are shown as function of τ-liquid of clouds, LWP and CFC changes. It is evident that the relationships between total CRF, τ, and LWP are more important in modulating radiation in JAS than in AMJ. This is the case when the underlying surface has still an albedo high enough to modulate CRF, as in spring months over regions with sea ice. With a decreasing surface albedo, as in summer months, SW CRF cooling dominates over LW CRF warming. As a consequence, Arctic regionality emerges from the clustering of the regions, especially in AMJ and to a lesser extent in JAS. In the last two decades the net radiative effect of clouds on the surface is decreasing. Clouds cool the surface when they diminish the net SW flux by more than they enhance the net LW flux. We note also that CFC changes modulate mainly the LW portion of cloud radiation in both seasons. In fact, the seasonal coefficients of determination r^2 of SW CRF by CFC trends is comparable to those by τ liquid trends. However, for the LW CRF, r^2 by CFC is higher than that by τ-liquid (CFC: AMJ 0.98 for both above ocean and all areas; JAS 0.87 above ocean 0.94 above all areas. τ-liquid: AMJ 0.39/0.02 above ocean/all areas; JAS 0.65/0.19 above ocean/all areas). This is the case when clouds become optically denser and hence more reflective.

R50

Line 350: Perhaps: "In the last two decades the net radiative effect of clouds on the surface is decreasing."

A50

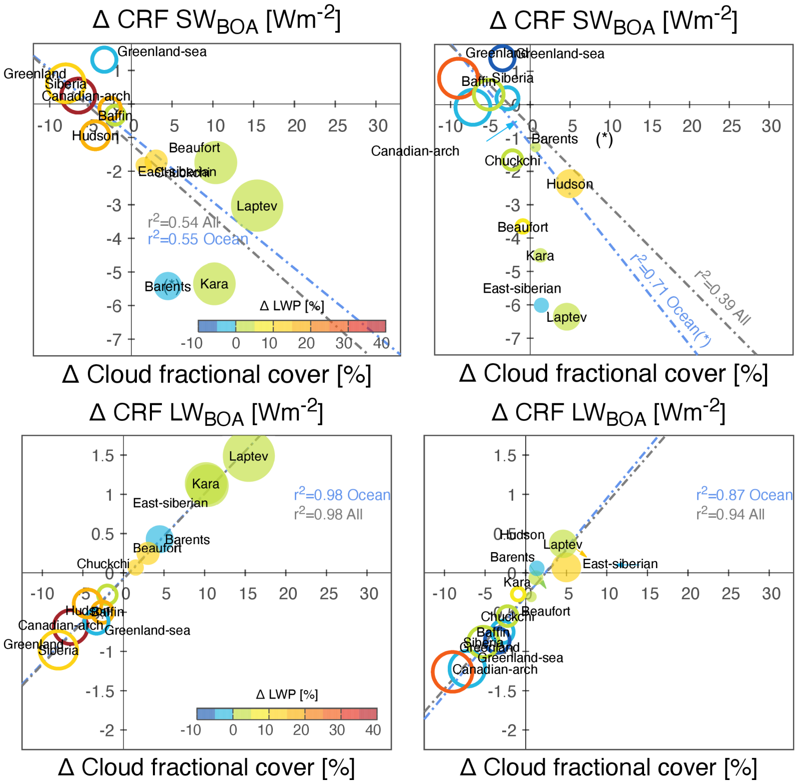

Fig. 13: Seasonal (left Apr-May-Jun ; Jul-Aug-Sep: right) of total changes [%] in cloud radiative forcing at the surface, cloud fractional cover and liquid water path.

Agreed.

R51

Line 351: Perhaps: "Clouds cool the surface when they diminish the net SW flux by more than they enhance the net LW flux." The original statement is not true as stated.

A51

Indeed. Agreed.

R52

Line 351-352: The above statement is simply true, regardless of any change in the clouds. It is possible that the SW CRF becomes MORE dominant over the LW CRF as the clouds become more optically thick and more reflective. This appears to be somewhat the case in JAS and not really in AMJ. Overall, these last three sentences of this paragraph need to be re-written in a way that accurately describes CRF, cloud effects, and the implications of changes in COT.

A52

We will clarify the relationship between reflectance, cloud properties and the radiative forcing keeping in mind also their changes.

C52

See C49.

R53

Line 353-367: One of the main points of the paper is that there are changes to the overall reflectance of the system that are NOT due to changes in CFC. But in this paragraph, there is a discussion about the sensitivity of CRF (SW, LW, and total) to changes in CFC. So, are changes in CFC important or not? And if not, why the lengthy discussion about this sensitivity?

A53

It is true that in this paper, we link observed changes in reflectance primarily to changes in cloud optical thickness and thermodynamic phase of clouds. Nevertheless, the changes in CFC are not of minor importance. First, because CFC and COT are radiatively related. Second, it is our intention to provide the reader with evidence and confidence in our satellite-derived calculations of CRF. One way forward is to compare our results with those in the literature, especially if the latter have been derived from in-situ measurement campaigns. In this respect, the results by Shupe and Intrieri (JCLIM, 2004) from the SHEBA campaign are a standard reference.

R54

Line 362-364: Sea ice retreat can happen earlier in some locations, such as the Barents. Leading to the unique values for the Barents seen in the AMJ panels of Figure 10.

A54

We agree with this comment and we shall add this information to the text.

R55

Line 364-367: Enhanced convergence of moisture could be a possible mechanism to explain why there might be changes in cloud properties (although this paper has not shown that there is a change in the total condensed cloud mass). However, changes in convergence of moisture are not needed to explain why the LW cloud effects dominate over the SW effects in AMJ. Regardless of any change in moisture convergence, cloud LW effects dominate SW effects in this season because the surface albedo is still high.

A55

This is surely true and we agree with the referee. Above the East Siberian, Laptev and Kara Seas, the sea ice extent and its albedo are high enough to explain the LW CRF over those regions in AMJ (see Fig. 9 of our manuscript).

However, we concurrently see an increase in CFC in the last two decades. Provided that the ocean can not be an appreciable source of water vapour in the boundary layer, Kapsch et al (2013) attribute an increased downwelling LW flux to the increased atmospheric opacity as a result of convergence of moisture, in form of clouds and/or water vapour (see Fig. 3-a in Kapsch et al, 2013) as seen in reanalysis data for April and May (but not in June). The water vapour trends are confirmed by Rinke et al. (2019), who show that water vapour is increasing in all three months of the AMJ season (see Fig. 5 of their paper).

While it is true that in our dataset (see A43) the CWP is either unchanged in AMJ and slightly decreasing in JAS over the regions discussed in this section, we think also that long-range transport of moisture might be a concurrent cause of the increase in LW CRF trend in these regions.

Kapsch, M.-L., Graversen, R. G., and Tjernstrom, M.: Springtime atmospheric energy transport and the control of Arctic summer sea-ice extent, Nature Climate Change, 3, 744–748, `https://doi.org/10.1038/NCLIMATE1884`, 2013.

Rinke, A., et al. "Trends of vertically integrated water vapor over the arctic during 1979–2016: Consistent moistening all over?." Journal of Climate 32.18 (2019): 6097-6116.
`https://doi.org/10.1175/JCLI-D-19-0092.1`

C55

(Lines 523–530) The warming effect from increased CFC in AMJ over these regions is directly linked to the retreat of sea ice, the onset of which is in late May (Smith et al., 2020), but also to the enhanced convergence of atmospheric water content originating from open Arctic oceans during years with anomalously low sea ice extent. Provided that the ocean can not be an appreciable source of water vapour in the Arctic boundary layer, Kapsch et al. (2013) attribute an increased downwelling LW flux to the increased atmospheric opacity as a result of convergence of moisture, in form of clouds and/or water vapour (Rinke et al., 2019). Our results imply that this mechanism is not only evident in the year-to-year variability of exceptional sea ice lows, but is also a long-term component at decadal time scales, during which atmosphere-ocean coupling effects are predominant.

R56

Line 372-373: This first statement is not true. The statement in question is speaking to why there is a trend towards decreasing net CRF. Indeed, there is more insolation in JAS compared to AMJ but that is true of every year of the analysis and it does not explain a temporal long-term trend in CRF.

A56

We agree with the referee that a long-term trend in CRF is not affected by changes in insolation in one individual season and claiming it makes no sense. We are putting into context the first statement at line 372 (" more insolation in the JAS months results in a more efficient SW scattering by cloud droplets") with the lines before (370-371) and namely we are comparing AMJ months with JAS months: "Although not surprising, we note that the AMJ changes in CRF do not correlate with either LWP or COT. In the JAS months, however, larger cloud optical densities and LWPs are matched by a decrease in CRF at the surface. This is the combined outcome of . . . ".

We will remove the first statement.

R57

The second statement is true and is a direct result of the Shupe and Intrieri figure 7. However, this mechanism would lead to a decreased net CRF (more cooling) even if the COT and LWP did NOT change. In reading through this paper, overall, it appears that the clouds have changed somewhat, although it is difficult to discern exactly how from the information provided. However, it is quite certain (although not shown here) that the surface albedo itself has decreased over areas where sea ice has retreated. This surface albedo change itself will lead to the observed trend in total CRF, and the potential change in clouds might serve to enhance or diminish this direct impact of the decreasing albedo.

A57

We hope that with the help of A37, A43 and A49, together with the trends shown in Figs. 7 and 8 of the original manuscript, it will be clearer that cloud properties did change, and this has had an impact on the CRF at the surface.

R58

Line 376-384: Here again is a reference to changing CFC over Greenland. I suggest that the authors either remove all discussion of Greenland processes or spend the time to sort through the different perspectives. In this case Hofer et al. have draw some conclusions, and these tend to be in opposition to the conclusions drawn by Bennartz et al. This is in large part because Hofer et al. are talking about processes around the periphery of Greenland where decreased CFC will enhance the net surface SW and lead to enhanced melt. Bennartz et al. are talking about the middle of the ice sheet where clouds warm the surface nearly all of the time. A change in LWP there will perhaps warm the surface slightly more or less, but there will still be a warming effect. Much of the explanation in this paragraph does not make sense.

A58

We uphold our explanation, which is in fact not contrary to that given by the referee. Our intend to explain one of the most striking feature in our results, namely the increase in LWP and COT over Greenland and to relate it to CRF. We think that at least one paragraph should be devoted in the text to an explanation of the phenomenon. In the specifics, we explain the trends in our Fig. 8 and Fig. 10 with the results of Bennartz el al. (2013).

On the other hand, we agree with the referee that fragmented information on Greenland shall be consolidated for the sake of readability. We propose to move the paragraph to the end of the sentence at line 340 (after "(Hofer et al., 2017)").

Furthermore, Hofer et al. (2017) did not only deal with the periphery of Greenland but did consider the ice sheet in his investigations of the CFC. With the help of the reflectances and cloud data we can particularly clearly confirm Hofer et al: on the one hand we see a loss of CFC in summer in the southern part of Greenland and, at the same time, a loss of CWP (both LWP and IWP). On the other hand, we do confirm an increasing trend in optical thickness of relatively thin clouds in this region (see Table B1 in Appendix: τ-liquid AMJ 8.4 JAS 6.7, τ-ice AMJ 6.0 JAS 6.0), driven by the concurrent increase in LWP and IWP in both seasons. The paragraph will be replaced by the following text.

C58

(485 – 494) In addition to cloud loss (Hofer et al., 2017), extensive ice melt in Greenland is also known to be enhanced by low altitude liquid water clouds that have sufficient opacity to enhance downward LW flux, but are also optically thin enough to allow a significant amount of SW flux to pass through. This results in the surface being warmed (Bennartz et al., 2013). Such clouds occur in the LWP region between 10 $\mathrm{g\,m^{-2}}$and 60 $\mathrm{g\,m^{-2}}$. Figure 8 shows that the increase in τ-liquid of clouds and LWP over Greenland in spring and summer is among the largest in the entire Arctic (ΔLWP $>$ 20-40%). In both seasons, the cloud fraction decreases and τ-liquid (as well as the LWP) increases spatially on average.

Both effects impact upon the downward SW flux at BOA, but in the opposite direction, resulting in a small net positive change in SW CRF. For decreasing CFC and in presence of an increase in near-surface temperatures, we expect a decreasing downward LW flux larger than the enhancement by more liquid water in the clouds (see Fig. 9, mid panel).

. . .

(Lines 537–541) Overall, the radiative effect of CFC and τ is expected to be similar, provided that their changes in time agree in sign. Because CFC and τ change in opposite directions, the decreases in LW CRF and increases in SW CRF suggest a dominant influence of CFC rather than by water content in the clouds over Greenland. This CFC influence is still modulated, but not offset, by the changes in τ and CWP.

R59

Line 412: This statement is entirely dependent on season. The basic point is that, for a given amount of condensed mass, liquid clouds have a stronger interaction with atmospheric radiation than ice clouds. Thus, more liquid clouds at the expense of ice clouds in mid-summer will likely have an increased cloud cooling effect (particularly over low albedo surfaces) >>> this is the negative feedback. However, for the non-summer months (little to no insolation and generally higher albedo) that comprise most of the year, this change will simple enhance the cloud warming effect >>> positive feedback.

A59

We agree with the referee about the distinction between sunlit months and those without SW radiation. We will clarify this issue, bringing also into context recent literature (e.g. Huang et al, 2021). The latter shows that prescribing in the CESM1-CAM5 a weaker scavenging of supercooled liquid droplets by ice crystals via deposition in spring months leads to an increase in available atmospheric liquid water and a concurrent increase in downwelling LW flux at the surface.

Huang, Y., Dong, X., Kay, J.E. et al. The climate response to increased cloud liquid water over the Arctic in CESM1: a sensitivity study of Wegener–Bergeron–Findeisen process. Clim Dyn 56, 3373–3394 (2021). `https://doi.org/10.1007/s00382-021-05648-5`

C59

(Lines 570–581) When the cloud ice phase turns to liquid water a negative feedback is expected due to the offsetting of LW by SW. This is especially true in those months characterized by low surface albedo, by virtue of a stronger interaction with atmospheric radiation by liquid cloud droplets than ice crystals. For the rest of the year when the surface albedo is high and Sun illumination is low or absent, the cloud feedback is expected to be more positive, that is a warming effect. If climate models do not correctly capture this behaviour, i.e they do not incorporate more supercooled liquid and mixed-phase clouds (Lohmann, 2002), unrealistically large amounts of ice result, effectively contributing to the uncertainty in determining the sign of the net cloud feedback. We consider that this is one reason, which may explain in part the discrepancy between the atmospheric components (CAM) of the Community Earth System Model (Gettelman et al., 2019, Fig. 2). While Huang et al. (2021) show that prescribing in the CESM1-CAM5 a weaker scavenging of supercooled liquid droplets by ice crystals in spring months leads to an increase in available atmospheric liquid water and a concurrent increase in downwelling LW flux at the surface, we note that a CAM5 positive cloud feedback at Arctic latitudes becomes negative in CESM2-CAM6 as a result of an improved modeling of the cloud phase.

R60

Line 412-414: First, mixed-phase clouds are supercooled liquid clouds, they just also have some ice. Both have a similar impact on atmospheric radiation. Second, the statement about reversing the sign of the net cloud feedback lacks a lot of context. The seasonally-varying feedback described in the previous point exists now and into the future. It won't really be "reversed" because two of the primary determinants of the sign of the feedback are sun angle and surface albedo. Cloud properties might play some role in that, although this point has not been thoroughly demonstrated or quantified in the current paper.

A60

From our perspective, it remains important to distinguish supercooled liquid and mixed-phase clouds because of the microphysical interplay between the liquid and ice phases in the clouds. Moreover, the presence of some INP is needed to grow ice in the clouds and an accurate assessment of the Arctic aerosol loads and speciation is challenging. We briefly discuss this point in the context of future needs.

For the "reversal" of the cloud feedback, we agree with the referee that context is missing and the chosen wording is not optimal. Note that our intention in this paper is not to assess cloud feedbacks as a whole but to provide evidence-based support for modelling efforts. In this regard, we will provide more context with respect to the increased liquid content in the clouds and how this finding relates to changes in sea ice (Morrison et al., 2019), to Arctic cloud feedbacks (Sledd and L'Ecuyer, 2021b) and to the slowing of sea ice albedo feedbacks by clouds (Sledd and L'Ecuyer, 2021a).

Morrison, A. L., Kay, J. E., Chepfer, H., Guzman, R. and Yettella, V. (2018). Isolating the liquid cloud response to recent Arctic sea ice variability using spaceborne lidar observations. Journal of Geophysical Research: Atmospheres, 123, 473–490. `https://doi.org/10.1002/2017JD027248`

Sledd, A., and L'Ecuyer, T. S. (2021a). Emerging trends in Arctic solar absorption. Geophysical Research Letters, 48, e2021GL095813. `https://doi.org/10.1029/2021GL095813`

Sledd, A. and L'Ecuyer, T.S., 2021b. A Cloudier Picture of Ice-Albedo Feedback in CMIP6 Models. Frontiers in Earth Science, 9, p.1067. `https://doi.org/10.3389/feart.2021.769844`.

C60

(Lines 574–576) If climate models do not correctly capture this behaviour, i.e. they do not incorporate more supercooled liquid and mixed-phase clouds (Lohmann, 2002), unrealistically large amounts of ice result, effectively contributing to the uncertainty in determining the sign of the net cloud feedback.

. . .

(Lines 584–592) Nevertheless, an improved representation of supercooled liquid clouds in CAM6 models (McIlhattan et al., 2020) does not necessarily result in better accuracy in describing cloud feedbacks. Although there is consensus that clouds, twice as bright in CAM6 than in CAM5, increasingly reduce the amount of SW energy accumulated at the surface through optical thickness and phase feedbacks (Goosse et al., 2018), thereby slowing the Arctic sea ice albedo feedback by 5 years over oceans and 2 years over land (Sledd and L'Ecuyer, 2021a), there are indications that clouds might accelerate the albedo feedback in some CAM6 models (Sledd and L'Ecuyer, 2021b). This holds in summer months when the atmospheric contribution to Arctic TOA albedo, dominated by cloud reflectance, is higher than that of the surface. While suboptimal prescribed covariability of clouds with the underlying sea ice is not ruled out, Sledd and L'Ecuyer (2021b) indicate that future efforts should focus on understanding the parameterization of the cloud microphysics, especially for those models that show a decrease in atmospheric reflectance.

R61

Line 454-455: There are substantial differences in the standard deviation between GOME and SCIAMACHY. What does this say about the data and how does it impact the ability to detect the very small trends that are reported in the data?

A61

See A21 and C21

Overall: Based on my full assessment of the paper it is essential here to use the existing data to determine the answers to a couple of important questions that will help with interpreting the results: Is there a net change in condensed cloud mass (LWP+IWP) or is there simply a conversion of mass from ice to liquid? Is there a net change in CFC, or is there simply a conversion of ice clouds to liquid clouds? Is there a net change in total COT, or is there simply a conversion of ice COT to liquid COT? What is the impact on CRF (SW and total) of the observed changes in surface albedo, independent of any changes in cloud properties? The magnitude of this effect is important to understand as a context for any possible cloud changes that might also impact CRF.

We thank the referee for the time devoted to the scrutiny of our work. We think that his contribution has pushed us to considerably improve the manuscript. We point the referee to those answers that address his remarks. We incorporate the answers in the conclusions for the sake of clarity.

1. *"Is there a net change in condensed cloud mass (LWP+IWP) or is there simply a conversion of mass from ice to liquid?"*

   A43: a conversion of ice mass to liquid mass has taken place, without substantially changing the total mass of condensed water in the clouds.

2. *"Is there a net change in CFC, or is there simply a conversion of ice clouds to liquid clouds?"*

   A30: CFC has not changed at pan-Arctic scale. There has been a regional conversion from ice clouds to liquid clouds.

3. *"Is there a net change in total COT, or is there simply a conversion of ice COT to liquid COT?"*

   A43: Total COT has remained unchanged at pan-Arctic scale. COT liquid has increased while COT ice has decreased at pan-Arctic scale as well as at a regional scale.

4. *"What is the impact on CRF (SW and total) of the observed changes in surface albedo, independent of any changes in cloud properties?"*

   A37: The impact on CRF of the change in surface albedo (through sea ice concentration changes)

is to enhance SW CRF (more cooling). From sea ice areas to open water, the relationship between SW CRF and sea ice concentration, thus to surface albedo, is close to linear (Fig. 9, left panels). We hypothesize that the spread around this relationship is mainly driven by changes in cloud properties.
Based on Fig. 9, the total CRF turns from positive to negative (negative SW CRF > positive LW CRF) in the value range of sea ice concentration 60-80%.
At this stage, we consider that the analysis of instantaneous sensitivities, supported by models, is required to quantitively and comprehensively address the comment by the referee. This would allow to decouple the surface impact on CRF from that of the changes in cloud properties. We consider this beyond the scope of the actual paper.

Technical corrections . . .:

Thanks. All updated.