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 $R_{1 \ldots n}$
2. Our answers are red and labelled as $A_{1 \ldots n}$. For each answer, we explicitly say how the text will be updated together with new figures, where appropriate.

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.
More precisely, 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 are disappointed in his overall assessment. We shall answer the issues the referee has raised. In the referee's review, no scientific topic-related objections were raised, i.e. about the magnitude or sign of the trends retrieved, the patterns and spectral behaviour of the reflectances, the cloud properties, and

cloud radiative forcing. Similarly, the adopted technical solutions and approach to data harmonization, the assessment of statistical significance or error propagation have not been discussed. The section "Discussion and conclusions" was not read.
The major criticism is that we have not written the paper in what the referee considers to be an understandable narrative. This was obviously not our intention. With few specific criticisms, it is more difficult for us to understand what should be revised.

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 a, hopefully thorough, 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

Whilst we accept the need for improvement of our paper and its introduction (also pointed out by the second referee), 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.

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

Whist we value the frankness of the reviewer and accept that improvements of the manuscript are needed, we do not share his view. We would have valued more specific criticisms. We consider it a pity that the referee did not read the complete manuscript as part of his scientific scrutiny.
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

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.

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.)

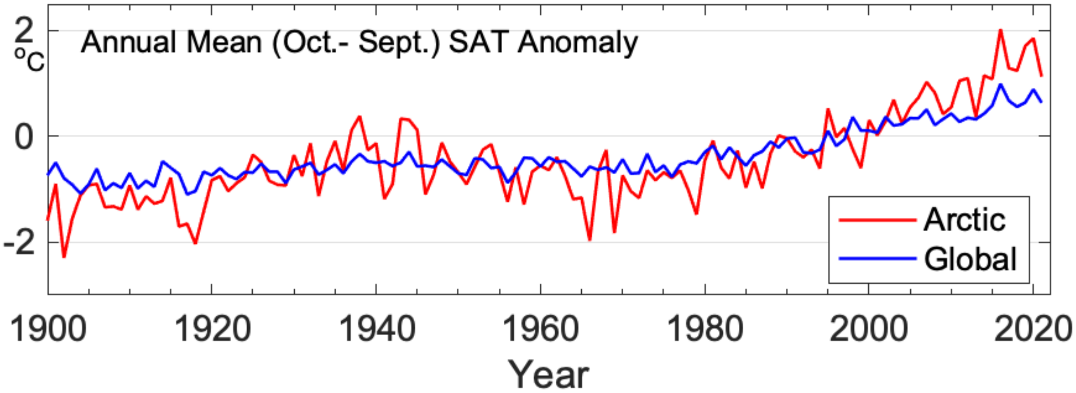

Fig. 1: Mean annual SAT anomalies (in °C) for weather stations located on Arctic lands, **60–90° N (red line)**, and globally (blue line) for the 1900–2021 period (n=122 years). Each temperature time series is shown with respect to their 1981–2010 mean. Source: CRUTEM5 SAT data are obtained from the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

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.

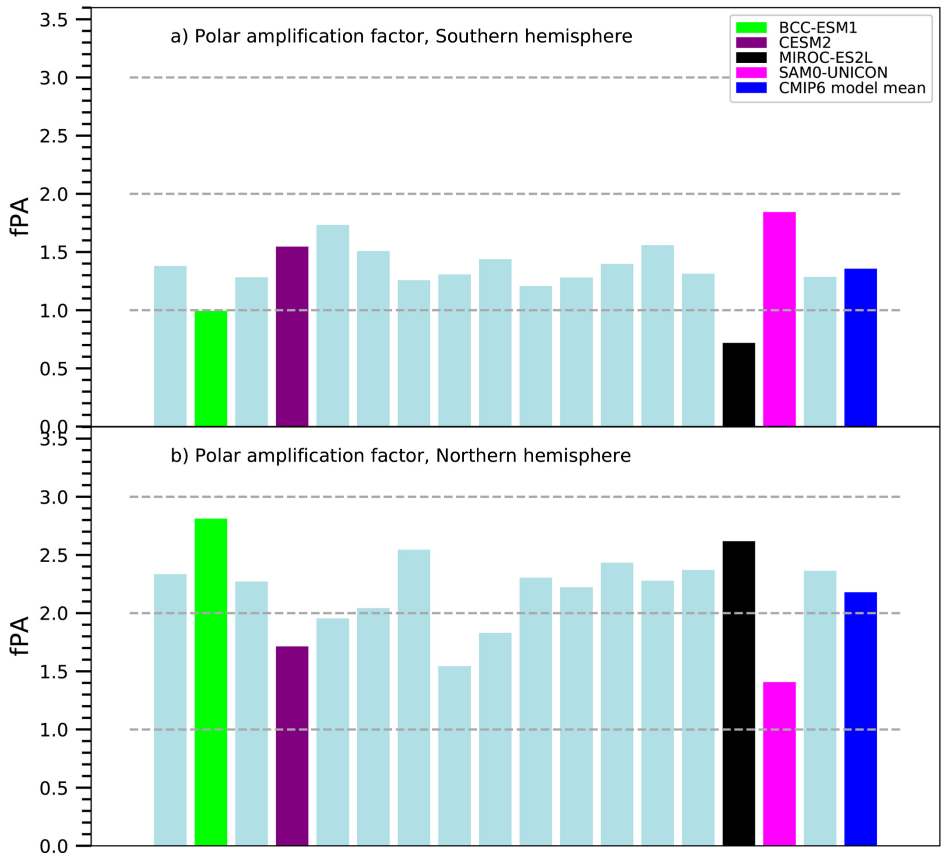

Fig. 2: Polar amplification factor from CMIP6 models (from Södergren and McDonald, 2022).

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.

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

Neither in the introduction nor in the discussion of our results, which has not been read (see R6), did we intend to exaggerate. It would have been more helpful for us if the referee would have given practical examples of where we exaggerated.

We regret the "*turn-off*" of the referee. Our aim was to provide a compelling message by logical reasoning based on evidence.

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: "This is in large part because the modulation of Arctic radiation by clouds in the shortwave (SW) and longwave (LW) is not well reproduced with state-of-the-art models due to the difficulty of modelling the cloud fields."

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 replace "rely on" by "are supported by".

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.

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.

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.

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.

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 plan therefore to make a major revision of the 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.

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.

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`

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 the retrieved 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 by describing the Figure with "A negligibly small and statistically insignificant downward trend of ...".

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. We will clarify this in the text.

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 use the following text: "The right hand side of the polar plots in the lower panel of Fig. 7 show seasonal trends in cloud albedo (CA) for AMJ and JAS. The magnitude of the positive trends in JAS is larger than those of AMJ but the spatial distribution of changes of the CA 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.

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.

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.

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. Ifft, 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.

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 split 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 its 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 with 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.