Referee #1

Previous title: Spring and summertime aerosol optical depth retrieval over the Arctic cryosphere by using satellite observations

Revised title #2: Retrieval of aerosol optical depth over the Arctic cryosphere during spring and summer using satellite observations

The authors would like to thank the reviewer for her/his interest and efforts to review our manuscript.

We hope that we have been able to answer satisfactorily the questions raised and clarify parts of the manuscript which were unclear or ambiguous.

We have changed the title of the manuscript to as per the first referee's suggestions.

In the following the referee comments and criticisms, our responses, as authors, and our resultant changes to the manuscript are colored black, blue and red respectively.

Q1: One of the main themes from the first-round review is whether or not this article fits in the scope of AMT. The author still didn't fully address this problem. AMT is meant for introducing new technique in measurements, if the article is only focus on validation and evaluation, plus analyses of aerosol distribution over the Arctic from satellite retrievals, there are many other articles out there for an article that is more "sciencey". However, in response to reviewer, the author emphasizes that there is new addition of algorithm development other than following Jafariserajehlou et al., (2019). If that is the case, then the paper is suitable for AMT, but the structure and the title need to reflect the content.

Response:

We would like to cite the aim and scope mentioned on the website of EGU/AMT journal as follows (last visited 08.09.2023): "*The main subject areas comprise the **development**, intercomparison, and **validation** of measurement instruments and techniques of data processing and information **retrieval** for gases, **aerosols**, and clouds.*".

For example, apart from other years, only in this year several articles were published with the specific focus on validation (such as Vinjamuri et. al., 2023; Baars et. al., 2023; Moallemi et. al., 2023; Gregor et. al., 2023; Ratynski et. al., 2023; Lerot et. al., 2023; Nyamsi et. al., 2023; Lange et. al., 2023; Garane et. al., 2023; Furlani et. al., 2023 etc.; see references at the end of this author's response).

In this context, we would like to briefly repeat the strategy/content of our manuscript:

> ***Step 1:*** *We presented an existing AOD retrieval algorithm (Istomina et al (2009)) published in 2009, which we improved by integrating a novel cloud identification scheme Jafariserajehlou et al., which is published a decade after in the year 2019.*

Step 2: *We used the approach from step 1 and further introduced a post-processing scheme which additionally helped in filtering unreliable AOD retrievals.*

Step 3: *Integrating step 1 and 2, and running the whole scheme for the period of AATSR observations led to significant improvements in the AOD retrieval. As a consequence, it was possible for the first time to run this integrated approach over a large part of the Arctic cryosphere. This prompted us to test the validity/quality on much larger scales than being done in the article of Istomina et al. (2009), leading to the results we have shown in our manuscript.*

We consider the integration of the individual steps as ***method development***. The method developed we called AEROSNOW. Consequently, a subsequent ***validation*** must show that the methodology delivers valid results. For this reason, we emphasize that this novel methodology and its test for validity fits very well with the aims and scope of the EGU/AMT journal.

In order to increase readability for the typical readership of the journal, we have made the changes in structure and the title of the revised manuscript as follows:

We have included the description of both large building blocks of the new scheme, i.e. Istomina et al., 2009 and Jafariserajehlou et al., 2019 into Section 2 "Data Sets and Algorithms" in the revised manuscript.

Further, we have added the description of the methodology into Section 3 "Methodology", in which we have specified the development of AEROSNOW scheme. For more clarity, we propose to add a flow chart of AEROSNOW in the revised manuscript. The flow chart of the building blocks of AEROSNOW is presented as Fig.1 below.

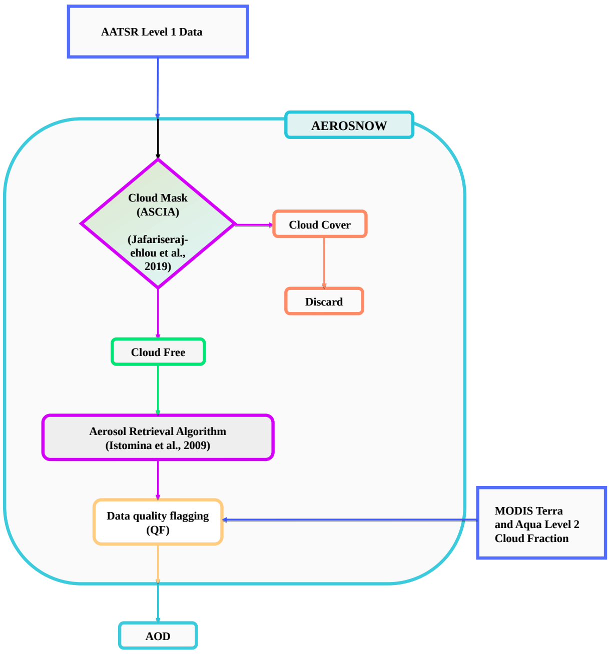

Fig.1 Flowchart describing the important building blocks of the AEROSNOW scheme.

We propose to change the manuscript title as follows: "Retrieval of aerosol optical depth over the Arctic cryosphere during spring and summer using satellite observations".

Q2: Assuming the latter scenario, here are the suggestions: 1. Move new development of AEROSNOW algorithm development out of section 2 and make it a new section. Because in Section 2 is meant to introduce already existing data and algorithm. Everything that is pre-existing can be in that section and the new addition should be in methodology or a section called algorithm new development. 2. Change the title. 3. Article spent a page introducing cloud mask. If it is from previous paper, the cloud mask introduction is needed, but can be summarized more concisely.
Response:
Referee's suggestion 1 and 2: We have followed the reviewer's recommendations and have made the structural changes that we outline in the text of our response to Q1.

Referee's suggestion 3: We have followed both of the reviewer's recommendations. Since the second reviewer suggests explaining the cloud masking approach (ASCIA) in more detail, we have summarized the cloud masking approach in Section 2.3.1 "Cloud detection Algorithm (ASCIA)".

Q3 (i): The second problem that still exist is the uncertainty estimates. Retrieving aerosol over ice/snow surface using passive sensor is extremely hard due to little information content within the TOA reflectance that is dominated by surface. Thus, a small error/assumption mismatch in surface will cause large error in aerosol retrieval. The article needs to show convincing results that the surface assumption is valid and give solid uncertainty estimation on surface introduced error. It is well known that snow grain size change drastically from fresh snow to aged snow to melting snow. The assumption assumes same snow grain size introduce large uncertainties over areas that new snow will deposit, or old snow will melt, which in Figure 2, the elevated aerosol near Greenland southern coasts, seems solid evidence of this type of error.
Response:
We thank the referee for acknowledging that the retrieval over bright surfaces is a difficult task.

We are aware that snow grain size variability, melt ponds, and impurities in the snow can cause problems. For this reason, we had to filter the data using the NDSI and apply the aforementioned post-processing. By taking these measures we were able to perform retrievals utilizing the (simple) BRDF parametrization according to Kokhanovsky and Breon (2012).

We believe that the outcome of our validation is precisely following your request for "convincing results that the surface assumption is valid".

The increased values of aerosols on the east coast of Greenland are located in the Fram Strait, which is characterized by strong ice export. We agree with the referee that this is a potentially problematic region, but for different reasons. The ice flows in this region might be in the size range of the instrumental spatial resolution and might not be correctly identified by the NDSI filter. Residual open ocean water fraction which is not identified by AEROSNOW might have an adverse effect on the retrieval quality.

However, there is also the possibility that the AOD values are accurate, as there is evidence that high wind speeds in this region can lead to sea salt emissions (Rhodes et al., 2017). For this reason, as suggested by the referee in Q1, we also compared the AEROSNOW data with the GEOS-Chem simulations (such as in AboEl-Fetouh et al., 2020/Hesaraki et. al., 2017, which is suggested by the referee as well in this review)

We found model-based evidence that high wind speeds increase the sea salt concentration in this area and might be responsible for increased AOD values (see Fig.3 below). In absence of high spatio-temporal validation data in this region, we can neither rule out that the data are problematic, nor that the high values are induced by specific processes, such as high wind speeds. Consequently we want to keep these data points.

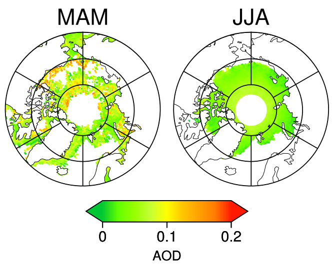

Fig.2 Mean climatological MAM and JJA AEROSNOW derived AOD over Arctic sea ice averaged from the year 2003 to 2011. White area shows lack of data apart from the masked land area.

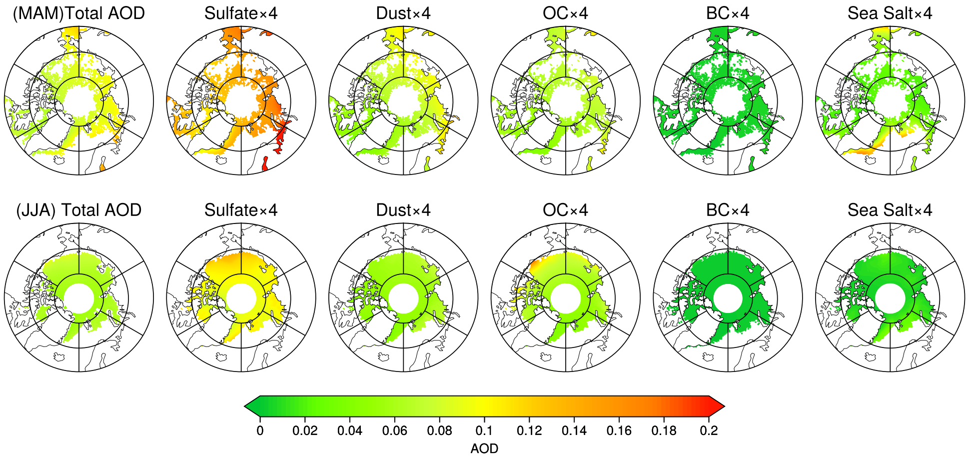

Fig.3 Seasonal mean of Spring (MAM, top panel) and Summer (JJA, lower panel) of GEOS-Chem simulated total and speciated AOD over Arctic Sea Ice averaged from the year 2003 to 2011 colocated with AEROSNOW. The simulation of GEOS-Chem are done as per Hesaraki et. al., 2017.

Q3 (ii): The article says BRDF introduced error is 30%, but I don't know how that is calculated or estimated.

Response:

To explain the error caused by the BRDF, the analysis performed by Istomina (2011) (described in section 3.3.3 in her publicly available dissertation) is used. Fig.4 shows the relationship between the simulated AOD and the input AOD with the blue solid line for the unperturbed case and the colored areas for the reflectances perturbed by 5%. A higher reflectance leads to a higher AOD and vice versa. It can be seen that a constant perturbation of the reflections by 5% does not lead to an offset type retrieval error, but to an error that increases with AOD. This means that, as expected, the assumption of a small atmospheric influence on the TOA reflection does not hold for larger AODs. However, the retrieval error can be assumed to be constant for an AOD below 0.30 (Fig.4), given a value of about ± 0.1 for the absolute AOD error.

Furthermore, for the calculation of the relative error according to Istomina (2011), it can be assumed that the retrieval error is constant for the AOD below 0.3. However, in our study, one of the highest retrieved value of AOD is 0.15, so for example for an AOD value of 0.15 we obtain a simulated AOD value of 0.115 (Fig. 4), resulting in a relative error of 30%.

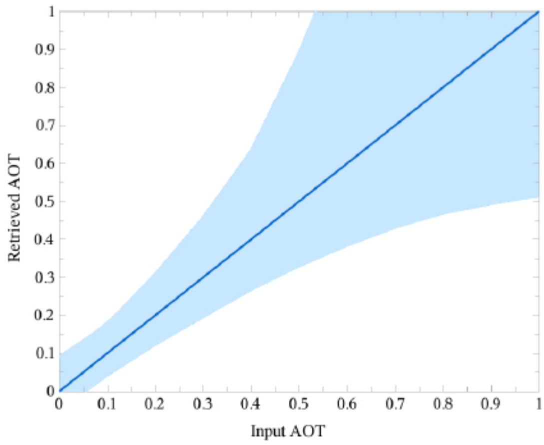

Figure 4: The dependence of the retrieved AOD on the input AOD for the RT-simulated TOA reflections, unperturbed (blue solid line), increased by 5% (upper edge of the color-filled area), decreased by 5% (lower edge of the color-filled area). Adopted from (Istomina (2011), section 3.3.3).

At line 246, we propose to modify:

For our study, a narrow interval of NDSI was required to limit the BRDF-induced error in retrieving the AOD, which is less than 30% using Istomina's approach (Istomina (2011), Section 3.3.3; Kokhanovsky and Breon, 2012).

Q3 (iii): The paper mentions that "The BRDF model is analytical and was compared with a series of multispectral and multidirectional measurements from the POLDER-3" However, it is not clear how are POLDER-3 TOA reflectance are guaranteed to be aerosol/thin clouds free. Also what is the result of the comparisons?

Response:

We apologize if the message was not clearly conveyed to the referee. The BRDF model used in the aerosol retrieval algorithm of Istomina et al. (2009) is from Kokhanovsky and Breon (2012). In their paper the authors validated the BRDF model with a series of multispectral and multidirectional measurements from POLDER-3. The authors ensured cloud-free conditions and verified the performance of the snow BRDF which was derived by a radiative transfer model for snow based on asymptotic solution. Such an approach is valid for a single scattering albedo of snow close to one (Kokhanovsky et al., 2011). Their results were validated using satellite measurements (POLDER) over the Arctic and Antarctic. It was found that the model can indeed be used to describe both the spectral and directional signatures of targets that are completely covered by snow. The deviations of the model from the measurements are less than 10%, and the correlation coefficients are above 0.85 in most cases analyzed over Arctic and Antarctica, although the model results are somewhat less anisotropic than the observations, especially in the forward scattering direction at large zenith viewing angles.

Q4: The third is that due to the limited AERONET site and their location, it is highly recommended author to compare the satellite retrieved AOD against field campaign results (e.g. POLAR-AOD, MOSAiC-ACA, and AFLUX - Arctic). Another points regarding using AERONET is that the uncertainty of AERONET AOD retrieval and aerosol property retrieval over polar region should be mentioned and discussed (Mazzola et al., 2012).

Response:

The valuable field campaigns mentioned by the referee such as POLAR-AOD, MOSAiC-ACA, and AFLUX-Arctic do not fall within our study period of 2003 to 2011, as follows:

1. POLAR-AOD:

- *The first POLAR-AOD campaign:* was performed at Ny-Ålesund (78 550 N, 11 560 E, Svalbard Islands, Norway) from ***March 25 to April 5, 2006 (11 days),*** near the Rabben station of the National Institute of Polar Research (NIPR, Japan). It was organized and hosted by the AWI German station.

  There are no colocations within 11 days measurement time period (***March 25th to April 5th, 2006)*** (Mazzola et. al., 2011).

- The second POLAR-AOD campaign which was held for intercomparison with the first one was performed over canary islands at 28°N latitude is thus not suitable. (Mazzola et. al., 2011).

2. MOSAiC-ACA:

- MOSAiC ACA took place from **28th August until 16th September 2020** (Mech et. al., 2022).

2. AFLUX/PASCAL – Arctic:

- AFLUX – Arctic airborne campaign took from March 20th to April 15th 2019, close to th Svalbard islands (Mech et. al., 2022).

- PASCAL– Arctic shipborne campaign took from March 20th to April 15th 2019, close to th Svalbard islands (Wendisch et. al., 2019).

For all campaigns/expeditions after 2011 we could not achieve temporal collocation.

Yes, we agree with the referee, the uncertainty of AERONET AOD retrieval over the polar regions has been discussed as per Mazzola et al. (2012) in the revised manuscript.
At Line 223 we propose to add:
The use of data sources other than AERONET for validation would have been very helpful. Unfortunately, data from valuable campaigns and expeditions such as POLAR-AOD (Mazzola et al., 2011), MOSAiC Expedition and MOSAiC-ACA (Mech et al., 2022), and AFLUX/PASCAL - Arctic (Mech et al., 2022) were only available after 2011. For this reason, we have focused on validation with ground-based AERONET measurements.

There are some other points in the paper that need to be addressed:

1. The aerosol model provide lack of size distribution, also the parameter is not wavelength dependent, leaving question whether the retrieval is a single wavelength retrieval or utilizes more wavelength. Also there are many other aerosol model study over the study region that provide more comprehensive dataset (e.g. AboEl-Fetouh et al., 2020).
Response:
In this study, we used 555nm for the retrieval of the AOD.

We would like to bring to the attention of the referee that the GEOS-Chem model simulation results used in AboEl-Fetouh et al., 2020 are taken from Hesaraki et. al., 2017. These research articles focused only on the Canadian Arctic region for the time period of 2009 to 2012 for 4 years. Further, in these two studies the focus was to compare GEOS-Chem simulated AOD with the AERONET retrieved AOD over the Canadian Arctic AERONET stations (such as Barrow, PEARL, OPAL, Resolute Bay, and Thule).

In our investigation, we have comprehensively examined a time frame spanning almost a decade, from 2003 to 2011, which involved extensive coverage of spatio-temporal central Arctic sea ice. In addition, we have incorporated data from the Hornsund AERONET station in our validation, in addition to the Canadian Arctic AERONET stations like PEARL, OPAL and Thule.

We agree with the referee that there are several model studies conducted over the Arctic. Mainly with the focus on understanding the uncertainties resulting from the direct effects and those on clouds, which are poorly represented in models (Boucher et al., 2013). The deficiency of many models is particularly true for the central Arctic sea ice region due to the lack of datasets with high spatiotemporal observational coverage and understanding of aerosols in this region (Schmale et al., 2021). It is worth noting that several valuable studies have been conducted for Arctic aerosols using models (such as Hardenberg et. al., 2012; Evangeliou et. al., 2016; Sand et. al., 2017; Breider et. al., 2017; Ren et. al, 2020; Schmale et. al., 2021). All of these important and valuable studies cannot use aerosol observations over the entire central Arctic cryosphere with high spatial and temporal coverage.

We therefore think, that the datasets generated in our study will help to improve model results related to aerosol loading in the high Arctic. We hope that they will also be used when creating new assimilated datasets in the central Arctic cryospheric region during ongoing Arctic warming.

The sparseness of available AOD datasets derived from observations may explain, at least in part, the variations of AOD simulations from different climate models (Sand et al., 2017). Without doubt, the lack of high spatial-temporally representative AOD measurements in the Arctic limits our knowledge about radiative forcing and the Arctic warming in global and regional climate models (Goosse et al., 2018).

2. What is the temporal resolution of the pre-constructed surface?
Response:
We have not used a pre-constructed surface, rather we used the BRDF model that reproduces the directional variations in the measured reflectance (Kokhanovsky and Breon, 2012), assuming a fixed snow grain size and snow contamination. This assumption is valid because the model is also able to reproduce the directional signature of snow, although its directional signature is very different from that of other types of surfaces such as vegetation or bare soil. A snow BRDF model was selected for our study and is explained in Eq. 3 to Eq. 10 of the revised manuscript.

3. It is not clear that whether the retrieval is done only on pure snow-covered area (e.g. 100% snow cover) vs. the percentage of snow is estimated using NDSI.
Response:
We would like to refer the referee to the line 189 of the manuscript as “Some corrections are needed in order to take the snow structure into account as only pure snow-covered area is used for the retrieval and in the real AATSR measurements.”

4. How are the data coverage impacted by solar zenith angle 75 degree cut off seasonally and spatially?

Response:

The effects of the solar zenith angle of 75 degrees cut off is shown in Fig. 2 of the manuscript. Fig. 2 of the manuscript is attached as Fig.5 of this author's response.

Because of the cutoff of the zenith angle of 75 degrees, aerosol retrieval coverage in March and October is spatially limited, as shown in Fig.2 of the manuscript as well as the Fig.5 of this author's response.

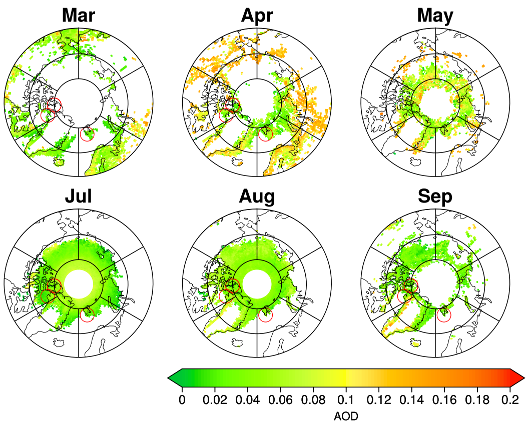

Fig.5. Pan-Arctic seasonal view of AEROSNOW retrieved AOD over snow and ice averaged from the year 2003 to 2011 for the months March to October, thus large parts of the period of insolation. Red circles indicate the location of AERONET stations

5. Paragraph 235 doesn't make sense and maybe better to place it where NDSI is introduced.

Response: We agree with the referee, we have moved the paragraph at line number 235 to 238 to line number 200 below the Eq.8.

We propose to move the paragraph at line 235 to line 200:

The NDSI is an index that refers to the presence of snow in a pixel and is a more accurate description of snow detection compared to fractional snow cover. Snow typically has a very high reflectance in the visible spectrum (VIS) and a very low reflectance in the shortwave infrared (SWIR). Snow coverage is determined by the NDSI ratio of the difference between the VIS and SWIR reflectance, and is defined in Eq. 13.

6. The filter of NDSI< 0.97 that is used to filter out 100% central Greenland isn't clear. Is there any reason for picking this 0.97? What does snow coverage looks like with different NDSI values? With that NDSI adjustment already included in SCF, is such a high value cut off using NDSI justified?

Response: *[The response to this question was described in Q5 in the authors response to referee #1 in our first round of answers and to Q3 in this round].*

To apply the approach at fixed snow grain size and account for potential snow contamination, we depend on snow cover. Moreover, the occurrence of snow in a pixel is established by NDSI, which offers a more precise depiction of snow detection as opposed to fractional snow cover (Riggs et al., 2017). Snow generally reflects the visible spectrum (VIS) quite well and exhibits low reflectance levels. Reflectance in the shortwave infrared (SWIR). The NDSI is calculated as the ratio of the difference between the visible (VIS) and SWIR reflectance: NDSI = ((bandvis - bandswir) / (bandvis + bandswir)). A pixel exhibiting an NDSI > 0.0 is indicative of snow cover, while a pixel with an NDSI <= 0.0 represents a snow-free ground surface (Riggs et al., 2017). The determination of the seemingly arbitrary threshold value of 0.97 was based on the validation process, which revealed clear over- or underestimations of the AOD when located over non-adequate surfaces.

In this study, the NDSI was used in a rigorous post-processing scheme to filter out the mixed and snow-free regions to minimize the impact of the surface on the top of atmospheric reflectance (TOA), therefore minimizing the impact on AOD retrieval. Fig.6 of this author's response shows the spatial snow cover over the Arctic as different NDSI values.

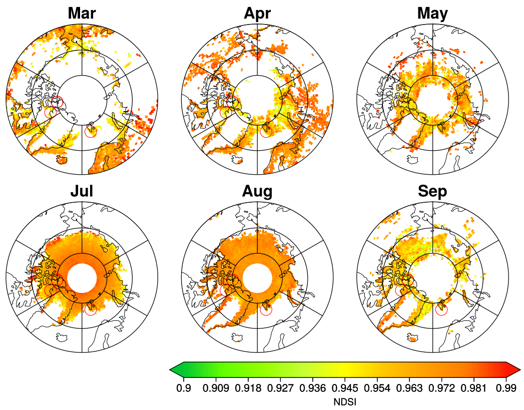

Fig.6. Pan-Arctic seasonal view of NDSI averaged from the year 2003 to 2011 for the months March to October, thus large parts of the period of insolation. Red circles indicate the location of AERONET stations.

7. Line 247 mentioned 30% less of BRDF-introduced error. The way this number is calculated isn't clear.

Response: *[We would ask the referee to read the author's answer to question Q3(ii), as we have already answered this question.]*

8. The uncertainty of MODIS cloud fraction over Arctic is not mentioned. It is expected to have large error (at least 10%) of CF over this region, with mostly missing thin cloud and cloud very close to the ground. How are these uncertainties impact the retrieval?

Response:

We agree with the referee. The MODIS CF products discrepancies with respect to Arctic has been discussed in the revised manuscript.

It is true that the CF from MODIS over the Arctic does not have the quality it usually has (Liu et al., 2022). However, it must be noted that this is part of the post-processing. A relatively reliable cloud masking has already been done using ASCIA. The post-processing shall be considered merely as an additional safeguard for the data. If it fails it induces additional loss of the data or can (also) not mask clouds (as ASCIA in one of the previous steps).

At line 250, we propose to add:

As per Liu et al.(2022) for the MODIS Terra and Aqua CF products over the Arctic, the discrepancies caused by different sensors and different algorithms are ±2% and ±5% with respect to the International Arctic Atmospheric Observing Systems (IASOA). The exact locations of the IASOA observatories are shown in Fig. 1 of (Uttal et al., 2016).

9. Figure 2 shall include another map of number of data points.

Response:

We agree with the referee. We have added the map of number of data points in the revised manuscript.

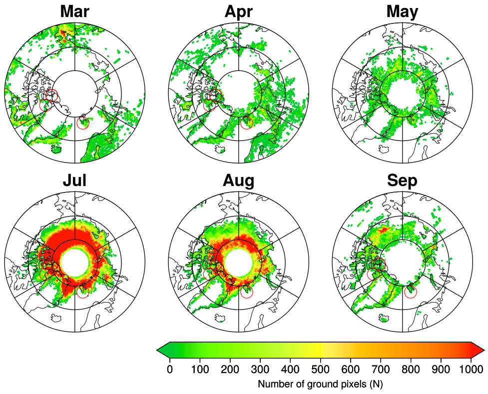

Fig.7. Pan-Arctic seasonal view of number of pixels used for calculating average AOD, averaged from the year 2003 to 2011 for the months March to October, thus large parts of the period of insolation. Red circles indicate the location of AERONET stations.

We propose to add map of number of data points presented above in the Fig.7 (in the manuscript as Fig. 4b) of the manuscript.

At line 267, we propose to modify:

The spatio-temporal frequency of observations over the Arctic from both ground and satellite is greater in summer (JJA) than in spring (MAM). Fig. 4(a) shows the monthly averaged AOD over snow and Arctic ice for the period 2003-2011, with significant differences in the spatial distribution of AOD. Fig. 4(b) shows the number of pixels used to average AOD per grid cell during 2003-2011 for March through October.

10. Is the reduced major axis method results significantly differ from normal linear fit? Although there is measurement error in AERONET, compared to satellite retrieved AOD, the measurement error in AERONET is almost negligible. Thus, the regular linear fit is also appropriate.

Response: *[A similar question has been raised by the 2nd referee in the first round of review. We post here our answer.]*

The reduced major axis (RMA) regression takes into account the uncertainties (or errors) on the two variables, while the ordinary least squares (OLS) regression takes into account the uncertainties on one variable. Here we are looking for the best linear agreement between the two variables (which must be the same regardless of the variable in X or in Y, therefore we are looking for a symmetrical relationship). For this, different methods are possible (for example by minimizing the perpendicular distance or the triangle), and we choose the RMA (so by minimizing the triangle).

This can be seen in the validation Figure 8 and 9 given below. For Hornsund and Thule AERONET station, the slope has increased from 0.71 and 0.88 in linear fit approach to 0.88, 1.01 in reduced major axis approach respectively.

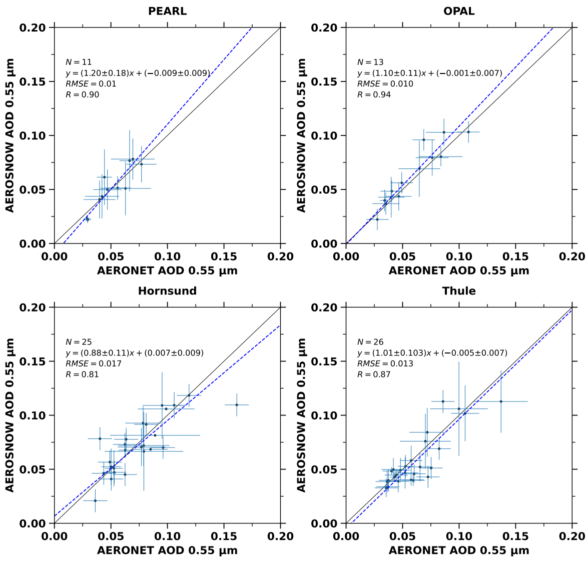

Fig.8. Validation of monthly mean AEROSNOW retrieved AOD colocated with monthly mean AERONET observation AOD obtained over PEARL, OPAL, Hornsund, and Thule stations. The linear regression lines are shown as blue dashed line (for reduced major axis approach)

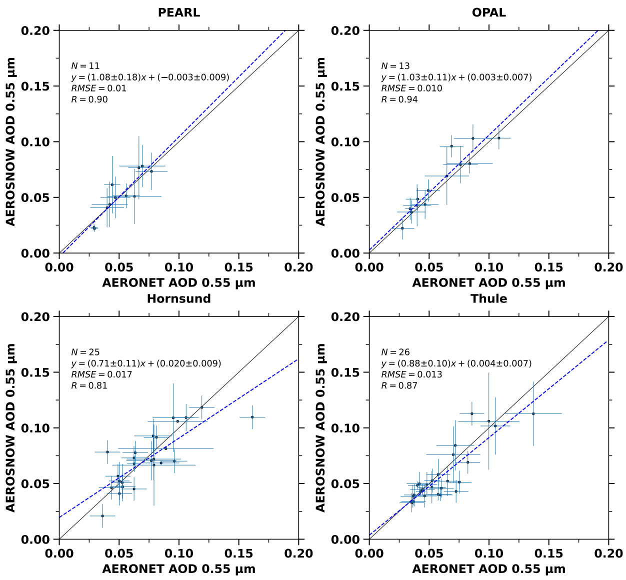

Fig.9. Validation of monthly mean AEROSNOW retrieved AOD colocated with monthly mean AERONET observation AOD obtained over PEARL, OPAL, Hornsund, and Thule stations. The linear regression lines are shown as blue dashed line (for normal linear fit approach).

11. Figure 6, the elevated aerosol loading in April is not shown within these three circles where AERONET located at. Elevated AOD exist at outside rim and there is no data to validate that.

Response:

There is a misunderstanding here. Unfortunately, we failed to point out that the red circles in Fig. 2 do not represent the radius of the collocation of 25km (they would have been much too small for visualization on the pan-Arctic map), but are only for orientation. To avoid such misunderstandings, we have added a note to the caption of Figure 2.

We propose to add in the title of the Fig.2:

Pan-Arctic seasonal view of AEROSNOW retrieved AOD over snow and ice averaged from the year 2003 to 2011 for the months March to October, thus large parts of the period of insolation. Red circles indicate the location of AERONET stations for guidance. The size of the red circles is not identical to the spatial collocation radius of 25 km, which we have used in the validation.

12. Line 314-323 that section that explains the identification of aerosol over sea ice should be in methodology.

Response:

We agree with the referee.

We propose to move the paragraph at line 314-323 to section 2.3.2 of the revised manuscript.

References:

- Vinjamuri, K. S., Vountas, M., Lelli, L., Stengel, M., Shupe, M. D., Ebell, K., & Burrows, J. P. (2023). Validation of the Cloud_CCI (Cloud Climate Change Initiative) cloud products in the Arctic. Atmospheric Measurement Techniques, 16(11), 2903-2918. https://doi.org/10.5194/amt-16-2903-2023.

- Baars, Holger, Joshua Walchester, Elizaveta Basharova, Henriette Gebauer, Martin Radenz, Johannes Bühl, Boris Barja, Ulla Wandinger, and Patric Seifert. "Long-term validation of Aeolus L2B wind products at Punta Arenas, Chile and Leipzig, Germany." Atmospheric Measurement Techniques Discussions 2022 (2022): 1-34. https://doi.org/10.5194/amt-16-3809-2023.

- Moallemi, Alireza, Robin Lewis Modini, Benjamin Tobias Brem, Barbara Bertozzi, Philippe Giaccari, and Martin Gysel-Beer. "Concept, absolute calibration and validation of a new, bench-top laser imaging polar nephelometer." EGUsphere (2023): 1-39. https://doi.org/10.5194/egusphere-2023-392.

- Gregor, Philipp, Tobias Zinner, Fabian Jakub, and Bernhard Mayer. "Validation of a camera-based intra-hour irradiance nowcasting model using synthetic cloud data." Atmospheric Measurement Techniques Discussions 2023 (2023): 1-24. https://doi.org/10.5194/amt-16-3257-2023.

- Ratynski, Mathieu, Sergey Khaykin, Alain Hauchecorne, Robin Wing, Jean-Pierre Cammas, Yann Hello, and Philippe Keckhut. "Validation of Aeolus wind profiles using ground-based lidar and radiosonde observations at Réunion island and the Observatoire de Haute-Provence." Atmospheric Measurement Techniques 16, no. 4 (2023): 997-1016. https://doi.org/10.5194/amt-16-997-2023.

- Wandji Nyamsi, William, Yves-Marie Saint-Drenan, Antti Arola, and Lucien Wald. "Further validation of the estimates of the downwelling solar radiation at ground level in cloud-free conditions provided by the McClear service: the case of Sub-Saharan Africa and the Maldives Archipelago." Atmospheric Measurement Techniques 16, no. 7 (2023): 2001-2036.https://doi.org/10.5194/amt-16-2001-2023.

- Lange, Kezia, Andreas Richter, Anja Schönhardt, Andreas C. Meier, Tim Bösch, André Seyler, Kai Krause et al. "Validation of Sentinel-5P TROPOMI tropospheric NO 2 products by comparison with NO 2 measurements from airborne imaging DOAS, ground-based stationary DOAS, and mobile car DOAS measurements during the S5P-VAL-DE-Ruhr campaign." Atmospheric Measurement Techniques 16, no. 5 (2023): 1357-1389. https://doi.org/10.5194/amt-16-1357-2023.

- Garane, Katerina, Ka Lok Chan, Maria-Elissavet Koukouli, Diego Loyola, and Dimitris Balis. "TROPOMI/S5P Total Column Water Vapor validation against AERONET ground-based measurements." Atmospheric Measurement Techniques 16, no. 1 (2023): 57-74. https://doi.org/10.5194/amt-16-57-2023.

- Furlani, Teles C., RenXi Ye, Jordan Stewart, Leigh R. Crilley, Peter M. Edwards, Tara F. Kahan, and Cora J. Young. "Development and validation of a new in situ technique to measure total gaseous chlorine in air." Atmospheric Measurement Techniques 16, no. 1 (2023): 181-193. https://doi.org/10.5194/amt-16-181-2023.

- Hesaraki, Sareh, Norman T. O'Neill, Glen Lesins, Aurometeet Saha, Randall V. Martin, Vitali E. Fioletov, Konstantin Baibakov, and Ihab Abboud. "Comparisons of a chemical transport model with a four-year (April to September) analysis of fine-and coarse-mode aerosol optical depth retrievals over the Canadian Arctic." Atmosphere-Ocean 55, no. 4-5 (2017): 213-229. https://doi.org/10.1080/07055900.2017.1356263.

- Mech, Mario, André Ehrlich, Andreas Herber, Christof Lüpkes, Manfred Wendisch, Sebastian Becker, Yvonne Boose et al. "MOSAiC-ACA and AFLUX-Arctic airborne campaigns characterizing the exit area of MOSAiC." Scientific data 9, no. 1 (2022): 790. https://www.nature.com/articles/s41597-022-01900-7.

- Liu, Xinyan, Tao He, Lin Sun, Xiongxin Xiao, Shunlin Liang, and Siwei Li. "Analysis of Daytime Cloud Fraction Spatiotemporal Variation over the Arctic from 2000 to 2019 from Multiple Satellite Products." Journal of Climate 35, no. 23 (2022): 7595-7623. https://doi.org/10.1175/JCLI-D-22-0007.1.

- Uttal, Taneil, Sandra Starkweather, James R. Drummond, Timo Vihma, Alexander P. Makshtas, Lisa S. Darby, John F. Burkhart et al. "International Arctic systems for observing the atmosphere: an international polar year legacy consortium." Bulletin of the American Meteorological Society 97, no. 6 (2016): 1033-1056. https://doi.org/10.1175/BAMS-D-14-00145.1.

- Schmale, Julia, Paul Zieger, and Annica ML Ekman. "Aerosols in current and future Arctic climate." Nature Climate Change 11, no. 2 (2021): 95-105. https://www.nature.com/articles/s41558-020-00969-5.

- Von Hardenberg, J., L. Vozella, C. Tomasi, V. Vitale, A. Lupi, M. Mazzola, T. P. C. Van Noije, A. Strunk, and A. Provenzale. "Aerosol optical depth over the Arctic: a comparison of ECHAM-HAM and TM5 with ground-based, satellite and reanalysis data." Atmospheric Chemistry and Physics 12, no. 15 (2012): 6953-6967. https://doi.org/10.5194/acp-12-6953-2012.

- Evangeliou, Nikolaos, Yves Balkanski, Wei Min Hao, Alexander Petkov, Robin P. Silverstein, Rachel Corley, Bryce L. Nordgren et al. "Wildfires in northern Eurasia affect the budget of black carbon in the Arctic–a 12-year retrospective synopsis (2002–2013)." Atmospheric Chemistry and Physics 16, no. 12 (2016): 7587-7604. https://doi.org/10.5194/acp-16-7587-2016.

- Sand, Maria, Bjørn H. Samset, Yves Balkanski, Susanne Bauer, Nicolas Bellouin, Terje K. Berntsen, Huisheng Bian et al. "Aerosols at the poles: an AeroCom Phase II multi-model evaluation." Atmospheric Chemistry and Physics 17, no. 19 (2017): 12197-12218. https://doi.org/10.5194/acp-17-12197-2017.
- Breider, Thomas J., Loretta J. Mickley, Daniel J. Jacob, Cui Ge, Jun Wang, Melissa Payer Sulprizio, Betty Croft et al. "Multidecadal trends in aerosol radiative forcing over the Arctic: Contribution of changes in anthropogenic aerosol to Arctic warming since 1980." Journal of Geophysical Research: Atmospheres 122, no. 6 (2017): 3573-3594. https://doi.org/10.1002/2016JD025321.
- Ren, Lili, Yang Yang, Hailong Wang, Rudong Zhang, Pinya Wang, and Hong Liao. "Source attribution of Arctic black carbon and sulfate aerosols and associated Arctic surface warming during 1980–2018." Atmospheric Chemistry and Physics 20, no. 14 (2020): 9067-9085. https://doi.org/10.5194/acp-20-9067-2020.
- Rhodes, Rachael H., Xin Yang, Eric W. Wolff, Joseph R. McConnell, and Markus M. Frey. "Sea ice as a source of sea salt aerosol to Greenland ice cores: a model-based study." Atmospheric Chemistry and Physics 17, no. 15 (2017): 9417-9433. https://doi.org/10.5194/acp-17-9417-2017

Referee #2

Previous title: Spring and summertime aerosol optical depth retrieval over the Arctic cryosphere by using satellite observations

Revised title #2: Retrieval of aerosol optical depth over the Arctic cryosphere during spring and summer using satellite observations

The authors would like to thank the reviewer for her/his interest and efforts to review our manuscript.

We hope that we have been able to answer satisfactorily the questions raised and clarify parts of the manuscript which were unclear or ambiguous.

We have changed the title of the manuscript to as per the first referee's suggestions.

In the following the referee comments and criticisms, our responses, as authors, and our resultant changes to the manuscript are colored black, blue and red respectively.

I appreciate the effort of the authors in addressing my previous comments. However, in my opinion, the manuscript still has significant issues.

Q1: I asked the authors to give more actual details about the algorithm that was developed. The authors have added more text to the section 2.1.2. but many of the additions are just some results not really suitable for the method development part of the manuscript and citations without any details given. For example: "We set this value to ±30 min in this study (Jafariserajehlou et al., 2019), while cloudy or partly cloudy scenes exhibit much greater spatial and temporal variability." Without good knowledge on work by Jafariserajehlou et al. I do not understand what is meant here. The authors also give some results with no further details, for example on what region/stations and time were used. An example: "The ASCIA cloud detection algorithm achieved promising agreement of more than 95% and 83% within ±2 and ±1 okta, respectively, compared to ground-based synoptic surface observations (SYNOP) (WMO, 1995)".

Response:

Your criticism and that of referee 1 led us to thoroughly revise the description of the methods section of this manuscript. For a better understanding, we briefly repeat the building blocks of our method (same text as the answer to Referee 1):

> ***Step 1:*** *We presented an existing AOD retrieval algorithm (Istomina et al (2009)) published in 2009, which we improved by integrating a novel cloud identification scheme Jafariserajehlou et al. (2019), which is published in 2019. The cloud detection algorithm is presented in Jafariserajehlou et al. (2019).*
>
> ***Step 2:*** *We used the approach from step 1 and further introduced a post-processing scheme which additionally helped in filtering unreliable AOD retrievals.*
>
> ***Step 3:*** *By integrating step 1 and 2 and running the whole scheme for the period of AATSR*

observations led to significant improvements in the AOD retrieval. As a consequence, it was possible for the first time to run this integrated approach over a large part of the Arctic cryosphere. This prompted us to test the validity/quality on much larger scales than being done in the article of Istomina et al. (2009), leading to the results we have shown in our manuscript.

For more clarity, we propose to add a flow chart of AEROSNOW in the revised manuscript as follows:

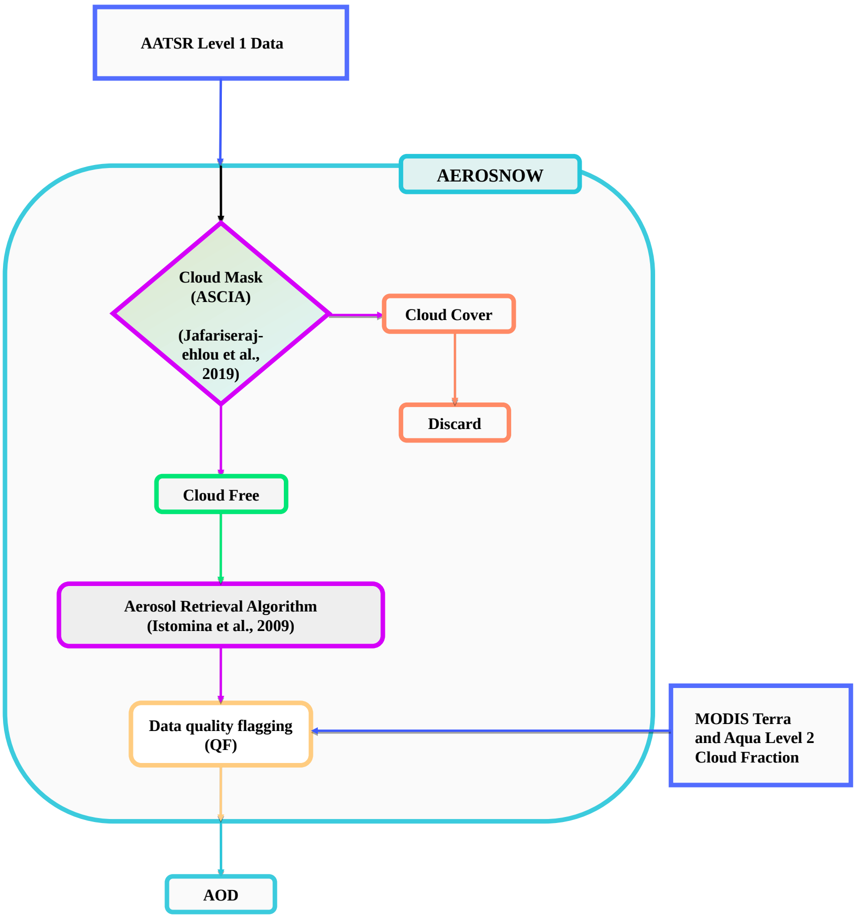

Fig.1 Flowchart describing the important building blocks of the AEROSNOW scheme.

More details on cloud masking (ASCIA) and the AOD retrieval are given in dedicated subsections of section 2.3. The integration of the individual building blocks (as illustrated in the flowchart shown above) is described in a new section 3 "Methodology".

Regarding your question concerning ASCIA: In this study, cloud-free scenes are assumed to be unchanged or only slightly changed for a given sampling period of ±30 min, while cloudy or partly cloudy scenes exhibit much greater spatial and temporal variability as per (Jafariserajehlou et al., 2019).

The cloud fraction retrieved by ASCIA has been validated with SYNOP (WMO, 1995) ground-based cloud fraction measurements for the time period of AATSR (the year 2003 to 2011) and

SLSTR (the year 2018). The World Meteorological Organization (WMO) established SYNOP stations for weather information around the world. The locations of the SYNOP stations used for the ASCIA validation within the Arctic circle are shown in Fig. 1 of this author's response, as well as added below.

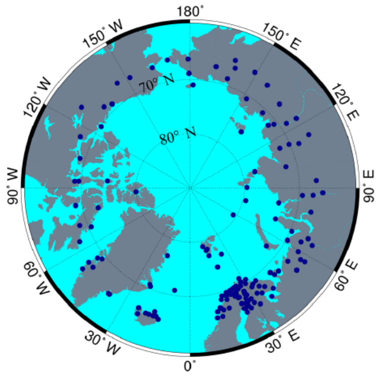

Fig.1 SYNOP network coverage over the Arctic, the dark-blue points indicate the location of SYNOP stations (adopted from Jafariserajehlou et al. (2019)).

We propose to change the manuscript title as follows: "Retrieval of aerosol optical depth over the Arctic cryosphere during spring and summer using satellite observations".

Q2: The authors also give some statements that are not justified in any way and therefore cannot be verified. Example: "In general, ASCIA shows better performance in detecting clouds in a ground scene observed at high latitudes than other algorithms applied to AATSR measurements."

Response:

We refer to the assessment performed in Jafariserajehlou et al. (2019) where the ASCIA cloud detection algorithm achieved promising agreement of more than 95% and 83% within ±2 and ±1 okta, respectively, by comparison with ground-based synoptic surface observations (SYNOP) (WMO, 1995). In general, ASCIA shows better performance in detecting clouds in a ground scene observed at high latitudes than other algorithms applied to AATSR measurements (Jafariserajehlou et. al., 2019).

We have added the description of the cloud identification algorithm of Jafariserajehlou et al. (2019) into section 2.3.1 "Cloud detection Algorithm (ASCIA)" of the revised manuscript. In particular, at line number 184 of the revised manuscript we have added "The ASCIA cloud detection algorithm achieved promising agreement of more than 95% and 83% within ±2 and ±1 okta when compared with ground-based synoptic surface observations (SYNOP) (WMO, 1995) over the Arctic.".

Q3: Many of the details in section 2.1.2 are given in a way that it is not possible to follow. For example: "As a result, PCC values calculated between multiple pairs of data for ground scenes of the same area at different times provide an indication of whether the scene is cloud-covered or cloud-free". Based on "multiple pairs of data" it is impossible to say if the correlation was computed for AOD, surface reflectance, top-of-atmosphere reflectance or something else.

Response:

The PCC values calculate reflectance at the top of the atmosphere between multiple pairs of data for ground scenes of the same area at different times give an indication of whether the scene is cloud-covered or cloud-free.

In section 2.3.1 "Cloud detection Algorithm (ASCIA)" of the revised manuscript at line number 144 we added "Consequently, the P CC values are derived using sets of reflectances at TOA of the same area at different times, which give an indication of whether the scene is cloudy or cloud-free (Lyapustin et al., 2008)".

Q4: I also asked for the cost function to be minimized in the retrieval to be shown in the manuscript. In the revised manuscript, the authors write: "The actual retrieval is working on Equations 7 and 4, and is minimized with respect to the optical depth (tau) at 555nm as a cost function." I do not understand what is meant by "minimizing equations 7 and 4" and would not be able reproduce the algorithm based on the details given in the manuscript.

Response:

In the newly created section 2.3.2 “Aerosol retrieval Algorithm” of the revised manuscript we now presented the cost function as Eq.18.

Q5: "The reflectance thresholds for a 3.7μm channel were used in the second part of ASCIA." However, no values for the thresholding are given and I cannot say if the authors mean top-of-atmosphere reflectance or surface reflectance.

Response:

We have added a brief description of the cloud identification algorithm of Jafariserajehlou et al. (2019) in section 2.3.1 “Cloud detection Algorithm (ASCIA)” in the revised manuscript. At line number 165 to 170 of the revised manuscript we have added the thresholds for a 3.7μm channel used in the second part of ASCIA for the top of the atmospheric (TOA) reflectance.

Q6: Overall, the section 2.1.2 is very difficult to follow and understand. I feel that based on the details given in the manuscript, it is not possible to replicate the results of the manuscript. It may be possible that everything was carried out correctly and following good scientific practices but I can not verify them based on this documentation shown in the manuscript.

Response:

We are sorry if the section 2.1.2 was difficult to follow. We have made changes in the revised manuscript to improve readability according to our explanations to Q1.

Q7: Furthermore, all the changes the authors have listed as proposed changes in the reply to referee have not been done in the actual manuscript as mentioned in the reply. For example: "At the end of line 19, we propose to add: The Arctic has experienced a significant increase in near-surface air temperatures over the past three decades: the rate of temperature increase being about four times larger than the global mean (Rantanen et al., 2022). This phenomenon is known as Arctic Amplification (AA)." This change has not been done in the revised manuscript.

Response:

We are sorry for this. We have corrected the mistake in the revised manuscript. We carefully rechecked the revised manuscript and have not found any missing entries any more.

At line 22, we propose to modify:

The Arctic has experienced a significant increase in near-surface air temperatures over the past three decades: the rate of temperature increase being about four times larger than the global mean (Rantanen et al., 2022). This phenomenon is known as Arctic Amplification (AA).

Q8: The authors claim both in the original and revised manuscript: "Uncertainties due to both space and time sampling differences are minimized". To be precise, just by using a certain collocation protocol (25km + 30min) does not minimize the uncertainties due to space and time. Also, minimize uncertainties of what?

Response:

We would like to remove the sentence “Uncertainties due to both space and time sampling differences are minimized” from our revised manuscript.

At line 278, we propose to remove:

Uncertainties due to both space and time sampling differences are minimized.

Q9: Finally, the authors justify some of their findings by citing an another manuscript under review in ACP. The ACP manuscript is written by the same authors and there they cite this AMT manuscript under review. I find it problematic to submit two quite similar manuscripts to two different journals simultaneously and cross-cite between the manuscripts many times and justify selections and findings in the other manuscript by the non-reviewed results shown in the other manuscript.

Response:

We would like to remove the citations of our ACP manuscript (https://doi.org/10.5194/egusphere-2023-730) from this AMT manuscript.

We would like to bring to the notice of the referee that, our ACP manuscript (https://doi.org/10.5194/egusphere-2023-730) is very different from the AMT manuscript.

In our AMT manuscript we presented the method as well as validation for the retrieval of the AOD for the pan-Arctic cryospheric region.

Whereas, in our ACP manuscript, we used GEOS-Chem global 3D chemical transport model simulations to find out that whether the aerosol components originating from natural and anthropogenic sources are attributed to AEROSNOW retrieved aerosol distributions over pan-Arctic sea ice region with high spatio-temporal coverage.

In addition, we have also performed a large-scale analysis focusing on the more spatio-temporal overage with regional, seasonal and annual variability of AOD components originating from anthropogenic as well as natural sources. Further, we investigated the impact of smoke intrusion events due to biomass burning, and seasonal change in precipitation on the aerosol variability and more importantly aerosol composition over the central Arctic cryospheric region.

At line 302, we propose to remove the citation:

This difference can be explained by using a chemical transport model by separating the total AOD to aerosol components (Breider et al., 2014)

At line 344, we propose to remove the citation:

The high anthropogenic aerosol loading (Arctic haze events) due to long-range transport (Willis et al., 2018) over Arctic snow and ice is captured by the AOD determined by AEROSNOW.

At line 352, we propose to remove the citation:

The promising AOD results obtained with AEROSNOW indicate that these can be used to evaluate and improve aerosol predictions for various chemical transport models (Willis et al., 2018), especially over the Arctic sea ice in spring and summer for the important period 2003-2011, which is within the period of Arctic amplification.