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

Revised title: Retrieval of aerosol optical depth over the Arctic cryosphere during spring and summer using satellite observations: A validation and evaluation

The authors thank the referee for her/his effort, and time taken to review our manuscript. The valuable criticisms and comments have helped us to improve our paper. 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 make it more interesting to AMT's readership.

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: The article titled "Spring and summertime aerosol optical depth retrieval over the Arctic cryosphere by using satellite observations" provides an analysis of AEROSNOW-retrieved satellite aerosol optical depth (AOD) statistics and validation using AERONET data over the Arctic region from 2003 to 2011. However, the main objective of the study is not clearly defined. The introduction highlights the importance of AOD retrieval using passive sensors, which suggests an algorithm development focus, which is suitable for the AMT journal. Nonetheless, the majority of the article discusses the distribution of retrieved AOD over the Arctic region and comparisons against AERONET data, with a greater emphasis on understanding the AOD distribution during spring and summer. The content of the article would be better suited for journals with a stronger emphasis on scientific aspects rather than technical aspects, as found in AMT. If the article intends to evaluate the accuracy and uncertainty of the retrieved AEROSNOW AOD, further investigation into uncertainties and comparisons with field campaign data would be necessary.

Response: We regret that the description in lines 65 to 69 of the manuscript did not convey to the referee clearly enough our objectives. Our main objective of the study described in this manuscript is to retrieve the aerosol optical depth (AOD) over the pan-Arctic cryosphere using a novel optimized algorithm, AEROSNOW, applied to measurements of the reflectance at the top of the atmosphere, measured by AATSR, made from the low earth orbit sun synchronous satellite Envisat from 2003 to 2011. Previous studies, retrieving AOD using the measurements of passive remote sensing instrumentation from space by others do typically not provide values over the pan-Arctic cryosphere region. So far, earlier versions of the retrieval were used to test the ability to retrieve AOD above Spitsbergen/Svalbard. In this manuscript, we describe an improved algorithm originally developed in house at the Institute of Environmental Physics at the University of Bremen and published by Istomina et al. (2009, 2011). As we have retrieved AOD over the cryosphere throughout the Arctic, an extensive validation of the algorithm is required. The validation is presented in Section 3 of this manuscript.

We agree with the referee that a short description of the algorithmic concepts used in AEROSNOW and its recent improvements, which include, the coupling of novel cloud identification scheme described in Jafariserajehlou et al. (2019), would also improve the quality of the manuscript and its suitability for publication in AMT.

We have expanded the AEROSNOW description in Section 2.1.2 in the revised manuscript to include additional information about the *mechanics* of the algorithm. Section 2.1.2 from line 91 to line 141 has been rewritten in the revised manuscript. We would like to humbly ask the reviewer to re-read Section 2.1.2 in the revised manuscript.

The discussion of the spatial distribution and seasonal behavior of the retrieved AOD dataset was introduced for a specific reason: Although measurements over the central Arctic are sparse and knowledge about them is also limited, we had expectations about these distributions. In this regard, the purpose of examining these distributions was to gain further confidence in this new dataset and to test the distributions with respect to our expectations. For example, the AEROSNOW observation of increased pan-Arctic AOD values during spring is a clear confirmation that Arctic haze events were well captured by this dataset. We will also address our motivation to discuss the distributions in the revised manuscript.

Therefore, this AMT manuscript aims to strengthen the confidence in the AEROSNOW approach. However, the actual use and corresponding geophysical analysis of the obtained results has been presented in our another manuscript: The preprint is available in Atmospheric Chemistry and Physics Discussions (ACPD) (https://doi.org/10.5194/egusphere-2023-730).

Considering the above and our envisaged adjustments and additions, we strongly believe that AMT is a suitable journal for this type of work and this manuscript.

The AOD data obtained by AEROSNOW is well validated with the ground-based AERONET data over the high Arctic stations, and the AERONET data are considered to be of high quality ground based observations. Data from campaigns and other ground-based measurements would also have been useful for comprehensive validation. However, to the best of our knowledge, no public dataset is available that provides sufficient spatial and temporal statistics for our study period from 2003 to 2011 particularly over the snow- and ice-covered regions of the high Arctic. Unfortunately, the most valuable recent field measurements do not fall within our study period (such as, MOSAiC in 2019-2020, ACLOUD/PASCAL in 2017 (Wendisch et al., 2023), PAMARCMIPs in 2018 and 2021 (Nakoudi et al., 2018; Ohata et al., 2021)).

At the end of line 69, we propose to add: After retrieval and validation, we discuss the distribution of AOD over Arctic snow and ice in spring and summer, since ground-based or space-borne observational data on AOD covering the entire high Arctic cryosphere are limited. In this regard, the purpose of examining these distributions is to gain further confidence in this new data set and to test the distributions with respect to our expectations. For example, we examine whether the AOD retrieved by AEROSNOW is able to capture the increased pan-Arctic distribution of AOD in spring compared to summer (Willis et al., 2018), which would be a clear confirmation of whether or not Arctic haze events are well captured by this dataset.

Q2: Several significant sources of uncertainty are mentioned in the article but not adequately addressed. Firstly, cloud contamination poses a major uncertainty source, requiring further examination. Additionally, the assumption of a fixed snow surface parameterization is mentioned but not sufficiently analyzed. The article should discuss the uncertainties associated with these assumptions and explain why they hold true for the study region.
Response: This question is addressed in the answer to ***Q4*** *(for cloud)* and ***Q5*** *(for NDSI)* of the comments by the referee below.

Q3: In line 94-95, the author claims that the cloud identification algorithm meets the requirements for high-latitude AOD studies, but this statement requires a citation to support it. Additionally, the phrase "a given sampling period" in line 96 needs to be clarified since a larger time window could introduce risks to this assumption.
Response: We agree with the reviewer and propose to change the lines as mentioned below to clarify the reviewer's question. We have followed Jafariserajehlou et al. (2019) who have proven that the AATSR-SLSTR cloud detection algorithm (ASCIA) meets the requirements for high latitude AOD studies. See also the answers to **Q4** for additional details. Cloud-free scenes are assumed to be unchanged or only slightly changed for a given sampling period. The sampling period used in this study is ±30 minutes, while cloudy or partly cloudy scenes have much greater spatial and temporal variability.

At the end of line 95, we propose to add the citation: The AATSR-SLSTR cloud identification algorithm (ASCIA) meets the requirements for the high-latitude AOD study and uses a dedicated set of thresholds for radiation and time-series measurements (Jafariserajehlou et al., 2019).

Line 97, we propose to modify: Cloud-free scenes are assumed to be unchanged or only slightly changed for a given sampling period. 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.

Q4: Line 172 introduces the use of cloud fraction as a parameter in the quality flag, yet the uncertainty associated with cloud fraction over the Arctic region is not discussed. It would be valuable to explore whether the limited impact of cloud fraction is due to the large uncertainty associated with this parameter.
Response: The ASCIA data product (see above) was validated by comparison with independent observations, such as synoptic surface observations (SYNOP), AErosol RObotic NETwork (AERONET) data, and the following satellite products: (i) the ESA standard cloud product from the nadir cloud plume of AATSR L2; (ii) the product from a method based on a clear snow spectral shape developed at IUP Bremen (Istomina et al., 2010); and (iii) the Moderate Resolution Imaging Spectroradiometer (MODIS) products. Compared to the ground-based SYNOP measurements, ASCIA achieved promising agreement of more than 95% and 83% within ±2 and ±1 okta, respectively. In general, ASCIA shows better performance in identifying clouds over a ground scene observed at high latitudes than other algorithms applied to AATSR measurements.

At the end of line 97, we propose to add: 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). In general, ASCIA shows better performance in detecting clouds in a ground scene observed at high latitudes than other algorithms applied to AATSR measurements.

Q5: In line 118-119, the article mentions a fixed snow surface parameterization, the uncertainties related to this assumption should be analyzed and discussed. Specifically, it is important to explain why this assumption is valid for the study region, considering the Arctic's limited precipitation. Additionally, line 166 mentioned mixed snow regions, but its impact on AOD retrieval is not mentioned.
Response: To apply the fixed snow grain size approach and the assumption of snow contamination, we rely on the snow cover. Furthermore, the presence of snow in a pixel is defined by the Normalized Difference Snow Index (NDSI), 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 (Riggs et al., 2017). Snow typically has a very high reflectance in the visible spectrum (VIS) and a very low reflectance in the shortwave infrared (SWIR). The NDSI is defined as the ratio of the difference

between the VIS and SWIR reflectance, i.e., NDSI = (($band_{vis}$ - $band_{swir}$) / ($band_{vis}$ + $band_{swir}$)). A pixel with an NDSI > 0.0 is considered to have snow cover, while a pixel with an NDSI <= 0.0 represents a snow-free land surface (Riggs et al., 2017).

In this study, the NDSI was used in a rigorous post-processing of the datasets 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.

Further, NDSI alone cannot describe the reflective properties of the surface. Therefore, the bidirectional snow reflectance distribution function (BRDF) model is also used. The BRDF model reproduces the directional variations in measured reflectance with an RMS error that is typically 0.005 in the visible wavelength range (Kokhanovsky and Breon, 2012), assuming a fixed snow grain size and snow contamination.

Please note that the retrieval is based on Equation 7 in the revised manuscript, which uses the ratio of simulated nadir BRDF values for the nadir and forward views of the dual-viewing instrument AATSR. With this strategy, we mitigate absolute errors in the BRDF but rather rely on the *shape of the BRDF* as seen from both directions. 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% according to Istomina's approach (Istomina 2011, Section 3.3.3). Since we consider this error to be critical, we additionally introduced the Quality Flagging (QF) approach in our post-processing scheme, where we weighted the snow cover fraction even higher than the cloud fraction.

At the end of line 119, we propose to add: The BRDF model reproduces the directional variations in the measured reflectance with a root mean square (RMS) error that is typically 0.005 in the visible wavelength range (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.

At the end of line 166, we propose to add: The AEROSNOW retrieval is based on Equation 7 in the revised manuscript, which uses the ratio of the simulated nadir BRDF values for the nadir and forward views of the dual-viewing instrument AATSR. With this strategy, we mitigate the absolute errors in the BRDF but rather rely on the shape of the BRDF as seen from both directions. 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). Since we consider this error to be critical, we additionally introduced the Quality Flagging (QF) approach in our post-processing scheme by adopting independent additional support from MODIS Terra and Aqua cloud fraction (Ackerman et. al., 2007) apart from ASCIA cloud detection algorithm, where we weighted the snow cover fraction even higher than the cloud fraction.

Q6: Some additional points to address include providing information about the basic aerosol properties of the models used (e.g., single scattering albedo and asymmetry factor) in line 137. Furthermore, the impact of a solar zenith angle cutoff of 75 degrees mentioned in line 160 should be discussed in terms of its impact on data sampling, particularly if there are specific times within a season when aerosol retrieval is not possible. Additionally, all monthly plots should display the variation in data for both AERONET and AEROSNOW datasets, including the number of retrieved data points aggregated into the monthly data. Lastly, in line 233, Figure 8 is introduced before Figure 7, which should be corrected.
Response: The basic aerosol properties used in the model, such as single scattering albedo (SSA), real part, and imaginary part of the refractive index for the coarse and accumulation modes of water-soluble, oceanic, dust, and soot aerosol components, are given in Table 1 in the revised

manuscript, which is adopted from the Istomina et al. (2011). Further, to avoid possible inaccuracies associated with particle shape, in this work on Arctic aerosol satellite retrieval we used the phase function for 550 nm measured ground-based by the Alfred Wegener Institute for Polar and Marine Research during one Arctic haze event on 23 March 2000 at Spitsbergen, Ny Ålesund, Svalbard, 78.923°, N 11.923° E, instead of the asymmetry factor.

We follow the recommendations in Istomina (Istomina 2011, Section 3.3.5) for a solar zenith angle (SZA) cutoff of 75 degrees based on sensitivity analysis using the SCIATRAN radiative transfer model (see also Mei et al., 2023). We agree with the referee that such a cutoff of the SZA leads to below average light conditions where the retrieval is working at the limit of its feasibility. We have done this deliberately, because March, being an important haze-event month, is also having such low light conditions and would have been excluded when we would have filterered more conservatively. Thus, keeping March in this dataset is an approach to extract as much as possible from the data to provide the most comprehensive view for the scientific community. March is already a time when Arctic haze events are relevant. Keeping March in this dataset was an attempt to extract as much as possible from the data to provide the most comprehensive view to the scientific community. A similar argument applies to summer, when persistent cloud cover also has a significant impact on the representativeness of the data. In our approach, we have applied a compromise between data yield and statistical representativeness.

We revised Fig.4: The revised presentation in monthly data is shown in the figure below and is also added in the revised manuscript of Fig.4.

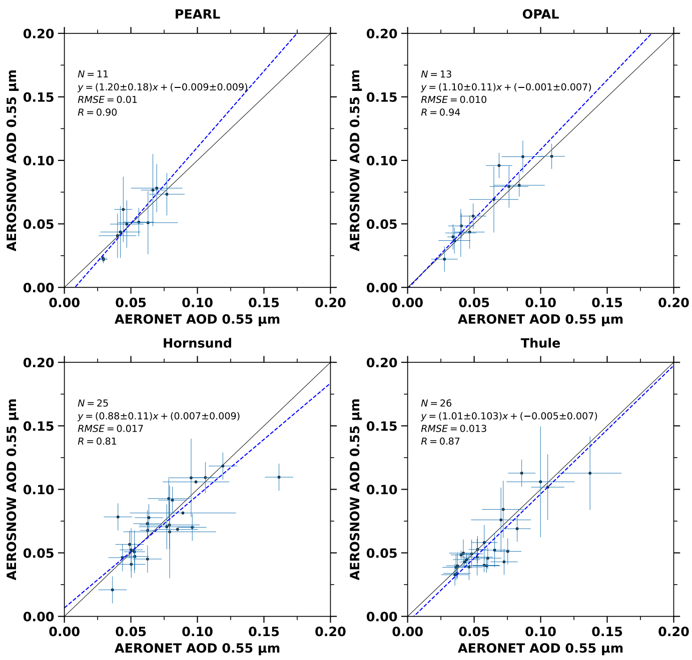

Figure 1: Figure 4. Validation of monthly mean AEROSNOW retrieved AOD colocated with monthly mean AERONET observation AOD obtained over PEARL, OPAL, Hornsund, and Thule stations. The linear regression lines are shown as blue dashed line and the bars are of one standard deviation.

Yes we agree with the referee, we will cite both Figure 7 and 8 in line 233 of the revised manuscript.

At the end of line 137, we propose to add: The basic aerosol properties used in the model, such as the single scattering albedo (SSA), the real part, and the imaginary part of the refractive index for the coarse and accumulation modes of the water-soluble, oceanic, dust, and soot aerosol components are given in Table 1 adopted from Istomina et al. (2011). Further, in this work, we used the phase function for 550 nm measured ground-based by the Alfred Wegener Institute for Polar and Marine Research during the Arctic haze event on 23 March 2000 at Spitsbergen, Ny Ålesund, Svalbard, 78.923°, N 11.923° E.

At the end of line 160, we propose to add: In this work, we adopted the recommendations in Istomina (Istomina 2011, Section 3.3.5) for a solar zenith angle (SZA) of 75 degrees based on sensitivity analysis using the SCIATRAN radiative transfer model (see also Mei et al., 2023).

We propose to change line 233: However, comparing the seasonally averaged climatology from 2003 to 2011, the AEROSNOW results indicate higher AOD in the spring, and smaller values in summer shown in Fig. 7 and Fig. 8, which was expected due to the Arctic haze events (Willis et al., 2018).

References:

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