Re-evaluation and Homogenization of Aerosol Optical Depth Observations in Svalbard (ReHearsol)

RCN Project No: 311250/E40 - ReHearsol Final Report

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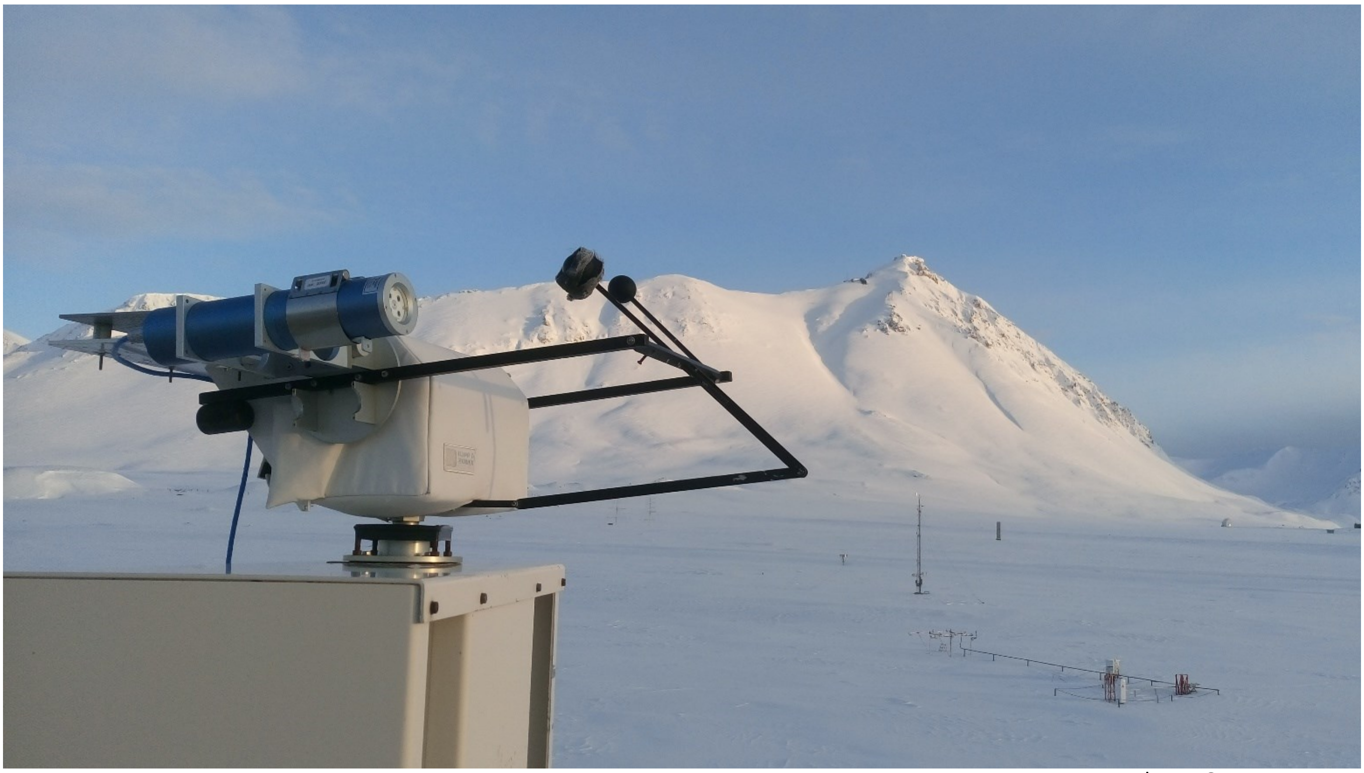

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ABSTRACT

The aim of this project was to collect, integrate and analyse observations of climate-relevant aerosol parameters (aerosol optical depth (AOD), Ångstrøm exponent (AE), black carbon (BC)) in and around Svalbard. These observations have been performed at different places and with different instrument types, the analysis procedures of which follow different protocols.

Annual merged datasets of AOD, AE and BC have been provided to the SIOS Data Management System and are now available for network-wide use in, e.g., Arctic climate and pollution studies. The analysis of the 2002-2020 data have confirmed earlier results showing a good correlation between measurements in Ny-Ålesund and Hornsund, but not a high degree of short-term agreement due to aerosol variability arising from geographical locations and local conditions. There is also a clear link between the columnar AOD/AE-measurements and in-situ aerosol measurements at Gruvebadet Observatory, while a comparison of in-situ measurements at Gruvebadet and Zeppelin Observatory shows deviations varying with season.

NORWEGIAN TITLE

Re-evaluering og homogenisering av observasjoner av optisk tykkelse av aerosoler på Svalbard (ReHearsol)

KEYWORDS

Aerosols	Arctic atmosphere	SIOS

ABSTRACT (in Norwegian)

Målet med dette prosjektet var å samle, integrere og analysere observasjoner av klimarelevante aerosolparametere (aerosoloptisk dybde (AOD), Ångstrøm-eksponent (AE), svart karbon (BC)) på og rundt Svalbard. Disse observasjonene er utført på forskjellige steder og med forskjellige instrumenttyper med analyseprosedyrer som følger forskjellige protokoller. Årlige datasett av AOD, AE og BC har blitt levert til SIOS Data Management System og er nå tilgjengelige for generell bruk i for eksempel arktiske klima- og forurensningsstudier. Analysen av dataene for 2002-2020 har bekreftet tidligere resultater med god korrelasjon mellom målinger i Ny-Ålesund og Hornsund, men ikke høy grad av kortsiktig samsvar på grunn av geografisk plassering og lokale forhold. Det er også en klar sammenheng mellom de søyleintegrerte AOD/AE-målingene og in-situ aerosolmålinger ved Gruvebadet Observatorium, mens en sammenligning av in-situ målinger ved Gruvebadet og Zeppelin Observatory viser avvik som varierer med sesong.

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Preface

The project "Re-evaluation and Homogenization of Aerosol Optical Depth Observations in Svalbard (ReHearsol) was enabled through a grant from the Svalbard Science Forum at the Research Council of Norway in the frame of its SSF Strategic Grants in 2020. The financial support from SSF/RCN is gratefully acknowledged.

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Summary

Summary of Scientific Achievements

The main goal of the ReHearsol project was to collect, inter-compare and quality-assure all observations of aerosol optical depth and black carbon in Svalbard and make them available to the SIOS (and wider scientific) community through the SIOS Data Management System. This has been achieved to a very large degree, except the optional additional data from Barentsburg and data from the new Pandora-instrument in Ny-Ålesund, as the algorithm for deriving AOD-data from this instrument is not yet available. A comparison of minute-resolution data from the longest time series (PFR and SP1A in Ny-Ålesund) resulted in the conclusion that the by far largest part of the data do not fulfil the WMO-criteria of sufficiently agreeing data sets, while the agreement between PFR and Cimel data in Ny-Ålesund (only 2017-2020) indicates that this criterion is reached. The discrepancies between the Cimel in Hornsund and the instruments in Ny-Ålesund are significantly larger, which is due to the large distance and resulting climatological differences. For these reasons, we decided not to produce one homogenized and merged Svalbard AOD data-set, but to collect all data in annual files (AOD at four wavelengths, multi-wavelength Ångström exponent, geographical coordinates for marine data). These data are provided to the SIOS Data Management System and its core data repository. A field study linking in-situ observations of black carbon at sea level and at the Zeppelin Observatory (475m a.s.l.) was performed in April 2021. Episodes of high AOD (> 0.15 @ 500nm) in the time period 2010 to 2020 were analysed with respect to their correlation to in-situ measurements of aerosol extinction, absorption and scattering at Gruvebadet Observatory. Such a correlation was found for most measurements, but not for the long-lasting episode in summer and autumn 2019.

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1 Scientific background and motivation

Measurements of aerosol optical depth (AOD) by means of sun photometers provide information about the total extinction of aerosols in the atmospheric column. This is of great importance for investigations of long-range pollution transport, mostly occurring in the free troposphere. A comprehensive overview of AOD and supplementary in-situ measurements of aerosols both in the Arctic and in Antarctica was given by Tomasi et al. (2007, 2015), while an in-depth study of AOD and BC at the three Arctic core sites (Ny-Ålesund, Point Barrow and Alert) in the period 2001-2011 was published by Stone et al. (2014). AOD measurements in Svalbard started in 2002 and have continued until today, i.e., a considerable part of the measurements including the more recent development of increasing summer aerosol load in the Arctic due to biomass burning, is not covered by the above publications.

A crucial element of AOD retrieval from sun-photometric measurements is the removal of (tropospheric) cloud-induced signals, but in polar regions also contributions from the stratosphere, e.g., from Polar Stratospheric Clouds, have to be considered. There is extensive collaboration and exchange between groups who have developed the various instruments and post-processing algorithms in use, and there are different routines both regarding data quality control and cloud flagging and regarding data aggregation routines (e.g., Kazadzis et al. 2018, Giles et al. 2019). Usually, these challenges are addressed in dedicated inter-comparison campaigns at particularly suitable sites with stable observation conditions, e.g., Izaña Observatory, Tenerife, Spain, for two of the instrument types involved in the ReHearsol project (Cuevas et al., 2019). However, at high latitude locations, inter-comparison results may differ from those at lower latitudes (Mazzola et al. 2012). Comparing three types of instruments and their respective evaluation routines at one high-latitude location thus offers a valuable contribution to data harmonization efforts in general. The value of such an exercise can be further enhanced by also including in-situ measurements of aerosol extinction, absorption and scattering as well as focused black carbon observations.

2 Objectives of the project

The main aim of ReHearsol was to revisit all AOD measurements performed so far in and around Svalbard in order to establish an optimized set of data, both with a high time resolution and aggregated data, and make these data available through the SIOS Data Management System (SDMS).
Sub-goals:

- Collect all AOD observations performed in Ny-Ålesund, Hornsund, possibly Barentsburg, and offshore so far;
- Systematically compare datasets from Ny-Ålesund village performed simultaneously at the highest possible time resolution; including new Ny-Ålesund AOD measurements (Cimel at AWIPEV, NILU Pandora at Sverdrup Station)
- Establish a unified AOD dataset for Ny-Ålesund by homogenizing AOD datasets (assessing calibration and retrieval differences among different instruments) and report on the uncertainty of the unified dataset);
- Compare Ny-Ålesund village observations with Zeppelin Observatory data, including both AOD and in-situ black carbon (BC) absorption measurements;
- Compare Hornsund Cimel observations with the Ny-Ålesund homogenized dataset;
- Link air mass directional clusters with AOD observations and identify local pollution and long-range transported pollution events;
- Propose a combined measurement strategy in order to minimize measurement gaps in the future.

3 Collection of data

In the frame of the ReHearsol project, the following data sets were collected:

- Sun photometer--Precision Filter Radiometer (PFR) observations at the Sverdrup Station, Ny-Ålesund, starting in April 2002, until May 2020, in 1-minute resolution (AOD at four wavelengths, AE derived from all wavelengths);
- SP1A sun photometer observations at AWIPEV Station, Ny-Ålesund, starting in March 2003, until October 2020 in 1-minute resolution (17 wavelengths until 2012, 10 wavelengths from 2013 to 2020; five selected for storage, AE calculated from 4 wavelengths);
- Cimel photometer sun observations at the Polish Polar Station, Hornsund, starting in April 2005, until October 2020 (4 wavelengths, 4-wavelength AE);
- Cimel photometer sun observations at AWIPEV Station, Ny-Ålesund, starting in June 2017, until September 2020 (4 wavelengths, 4-wavelength-AE);
- SP1A sun photometer observations at Zeppelin Observatory, Ny-Ålesund, from 2015, 2016, 2017, 2019, 2020 (10 wavelengths; 4-wavelength AE);
- Lunar Cimel measurements from AWIPEV Station in Ny-Ålesund for the period 2017 to 2019 (4 wavelengths, 4-wavelength AE);
- Lunar PFR measurements from Sverdrup Station, Ny-Ålesund for 2018 to 2020 (4 wavelengths, 4-wavelength AE);
- Microtops sun photometer observations on board R/V Oceania in 2007, 2009 – 2020, geographical area: 72 – 85°N, 0 – 50°E (4 wavelengths, 4-wavelength AE)
- Microtops sun photometer observations on board R/V Polarstern in 2009, 2012, 2015, 2017, 2020, geographical area: 72 – 85°N, 0 – 50°E (4 wavelengths, 4-wavength AE)

Black carbon measurements by means of a filter absorption photometer (PSAP-3W) taken by CNR at Gruvebadet, Ny-Ålesund, are available in 1-h resolution for the period 1 July, 2011, to 1 March, 2021, multi wavelength in-situ Aerosol absorption coefficient and equivalent black carbon measurements at Zeppelin Observatory, obtained by an aethalometer (AE-31, 7 wavelength) installed since 2001 by NCSR Demokritos, are available through NILU's EBAS database for the period 1 January 2005 – 1 September 2019.

All AOD measurements listed above except the SP1A measurements from Zeppelin Observatory have been grouped in annual files containing AOD data (4 wavelengths, SP1A: 5 wavelengths, 4-wavelength AE) at 1-minute resolution (only time slots where at least one observation value exists). This will enable a straight-forward access to data inter-comparison and further analysis.

3.1 Comparison of "down-town" Ny-Ålesund datasets

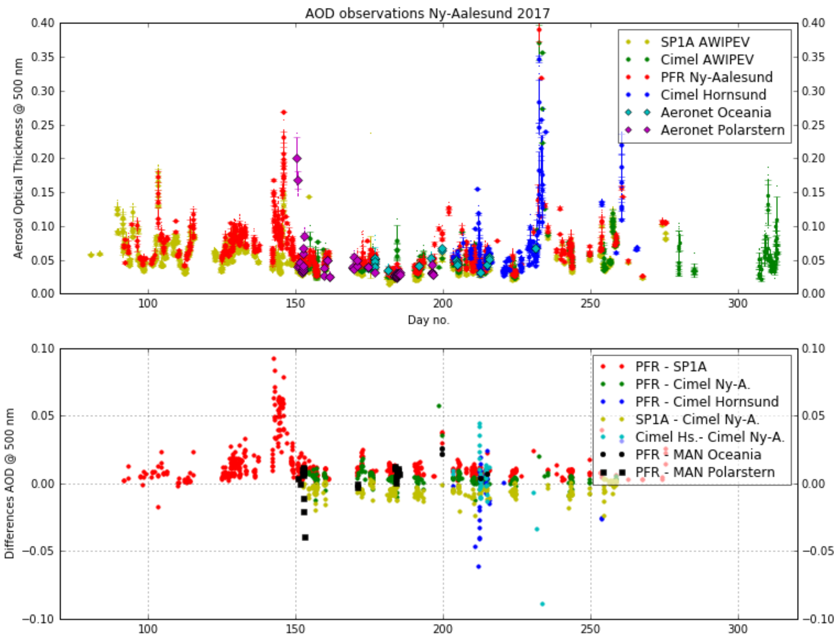

Figure 1: AOD (@500nm) measurements (hourly means with standard deviations) in 2017 at sea level (Ny-Ålesund, Hornsund, off-shore) (upper panel); absolute differences between selected pairs of simultaneous observation pairs (lower panel).

In the settlement of Ny-Ålesund, AOD observations have been performed at two observatories with a short distance between them: PFR since 2002 at Sverdrup Station and SP1A (initially from 1991; available data in ReHearsol since 2004) at AWIPEV Station. Since 2017, also a Cimel instrument has been in operation at AWIPEV with the aim that it will replace the SP1A sun photometer after a transition period with parallel operation. Figure 1 shows all AOD measurements in 2017 (upper panel) and a selection of (hourly means) differences between two data series where simultaneous measurements exist (lower panel). According to WMO report no. 162 (2005) measurements are sufficiently "equal if at least 95% of simultaneous measurements deviate from each other by less than ($0.005 + 0.010/m_{air}$)". A detailed comparison of the PFR and SP1A data sets revealed that this is not the case for these two instruments. E.g., the percentage of acceptable agreement varies between 6% in 2005 and 97% in 2020 at 500 nm. At other wavelengths the discrepancies are either smaller (862 nm) or larger (368, 412 nm) with best and worst agreements also occurring in other years. Median differences, 5th and 95th percentiles, % within WMO limit, numbers of points compared as well as correlation coefficients for all 17 years are summarized in Table 1; detailed annual values are available in a separate file.

Table 1: Statistics of deviations PFR – SP1A

	368nm	412 nm	500 nm	862 nm
No. of points	269,609	267,093	269,638	265,368
Median difference	0.002	0.007	0.006	0.001
5th percentile	-0.034	-0.029	-0.017	-0.017
95th percentile	0.023	0.031	0.026	0.017
% within WMO limit	51.4	40.0	48.3	68.7
Slope	0.981	1.000	0.917	0.836
Slope error	0.001	0.001	0.001	0.001
Intercept	0.000	-0.007	-0.001	0.004

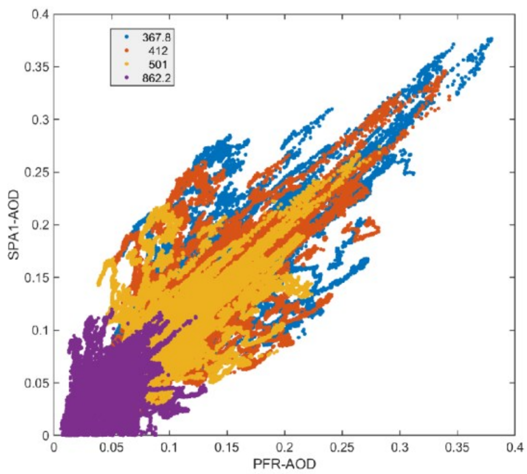

Figure 2: Simultaneous AOD measurements (PFR vs. SP1A) in the 2004-2020 time period.

	368nm	412 nm	500 nm	862 nm
Intercept error	0.000	0.000	0.000	0.000
Correlation coefficient	0.925	0.905	0.894	0.689

Correlations between the AOD values from PFR and SP1A for all years are shown for four wavelengths in figure 2. As figure 1 indicates, the differences are not homogeneous throughout the year, but highly variable with season during a year; the same is valid for the year-to-year variations.

Figure 1 also indicates that the agreement is better and more stable over time regarding PFR vs. Cimel (green dots vs. red dots in lowermost panel). The same is found for 2018 and, with limited numbers, in 2019 (few Cimel measurements) and 2020 (few PFR measurements). It should be noted, however, that although the datasets do not fulfil the very strict criterion of WMO for traceability, the observed median differences have a small impact on the long-term annual mean AOD.

3.2 Comparison of SP1A observations at AWIPEV and Zeppelin Observatory

Since 2015 sun-photometer measurements by means of an SP1A instrument have also been carried out at Zeppelin Observatory (Zep). Here we present a comparison for the year 2017, in which 25480 minutes of isochronal measurements are available during the whole sunlit season.

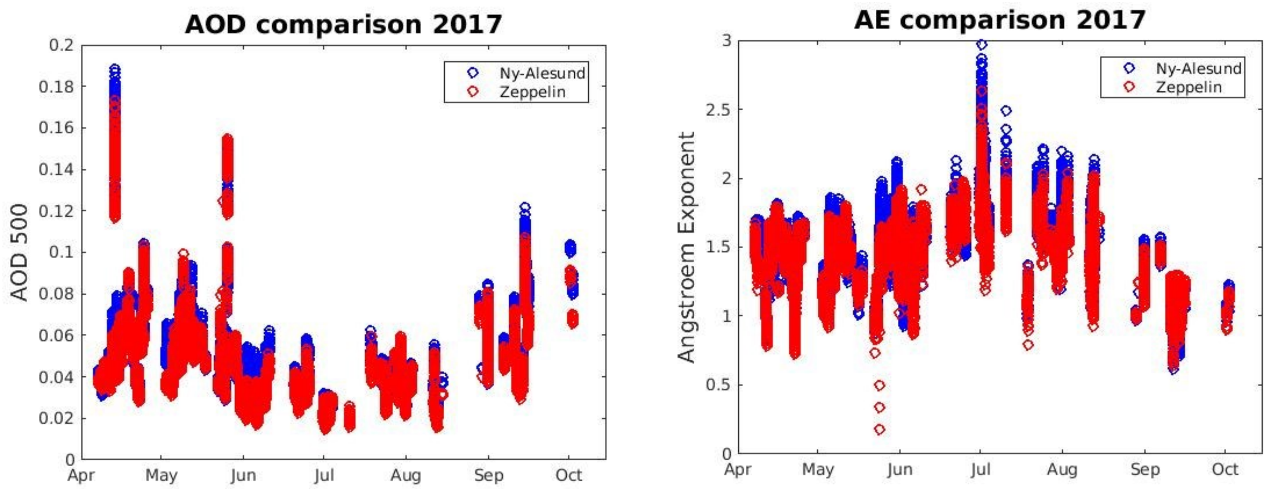

Figure 3: 2017 AOD at 500nm (left panel) and Ångström exponent (right panel) for Ny-Ålesund (blue) and Zeppelin Observatory (red).

The AOD at 500nm for both sites “Nya” (in blue) and “Zep” (in red) is shown in figure 3. One can see that in general the two data sets are very similar. The correlation between the two AOD500 data series over time is r= 0.9596, and at 368 nm it is even larger (0.9709).

The AOD absolute differences between both sites are small. At 500 nm the median AOD at Zeppelin Observatory is 0.0033 (7.55%) lower than in Ny-Ålesund. Only in 12.1% of all cases the AOD difference is larger than 0.01. Moreover, we found that the difference in AOD does not depend on the AOD itself. This means that observations at Zep do not simply miss a constant fraction of aerosol. Instead, based on this work, one can expect that the aerosol in-situ samplers at Zeppelin and at the “Gruvebadet” observatory near the village generally should measure the same aerosol in accumulation and coarse mode.

On the other hand, the Ångström exponent (figure 3) values reveal slight differences: Whenever the Ångström exponent (at Zep) is larger than 1.5 it is even higher at NyA, indicating that Zep is missing some of the Aitken mode particles from the ocean in summer.

3.3 Comparison of Hornsund Cimel data with Ny-Ålesund Cimel data 2017-2019

A comprehensive analysis of aerosol measurements in the Svalbard region in the years 2000 – 2015 was made in the PhD thesis of Dr. Paulina Pakszys (2018); a special focus on the comparison between Hornsund and Ny-Ålesund in the same period is given in Pakszys and Zielinski (2017). Both concluded with a generally high correlation between AOD observations at the two sites, however, with a bias towards slightly higher mean values and larger variability at Hornsund. These analyses were based on different instruments at the two sites, while from 2017 the same instrument type with identical calibration and analysis procedures (AERONET) became available allowing a direct comparison of AOD data falling in a window of ±1 minute at the two AERONET sites.

A total of 180 pairs of points were obtained in the period 2017-2019 (level 2.0 from AERONET), and the results are shown in figure 4. The statistics of the comparison show Mean Bias Error (MBE) values below 0.009 for all channels and Root Mean Square Error (RMSE) values ranging from 0.02 at 1020 nm to 0.29 at 340 nm. Overall, about half of the differences is within the WMO U95 limits in spite of the distance between two sites. However, the other half of the data prove that different aerosol conditions are being measured in the two sites. Generally, AOD values are slightly larger over Hornsund than over Ny-Ålesund.

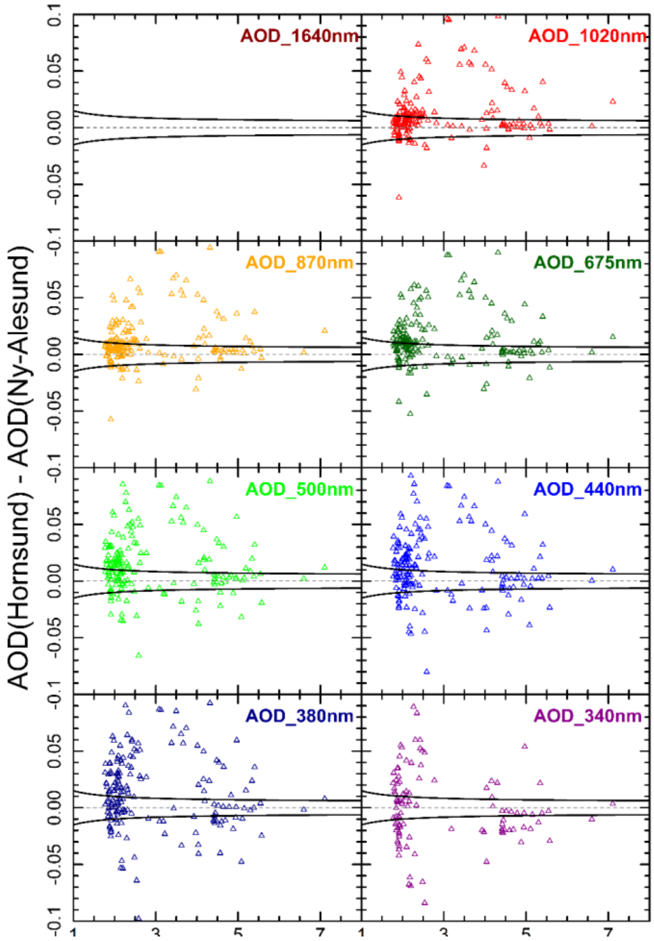

Figure 4: AOD differences between CIMEL instruments in Hornsund and Ny-Alesund versus optical air mass (m) in the period 2005-2015. Solid lines point out the U95 limits.

We also extended the analysis to the level 1.5 data of AERONET (upgraded to level 2 data shortly before the end of the project period); this increased the data basis to 849 pairs of points for the same time period. The results, not shown here, are in line with those obtained for the level 2.0. Almost half of the differences fall in the U95 limits, with no dependence on wavelength channel.

Therefore, we conclude that measurements at these two sites can help to assess aerosol conditions at a regional scale occurring over Svalbard.

4 Analysis of high-AOD episodes in the 19-year data record

Initially, a threshold value of 0.15 for AOD at 500 nm was chosen to identify high-AOD events. All hourly means larger than 0.1 and larger than 0.15 from all instruments were identified and stored in annual files. Moreover, annual files listing all single measurements of AOD(500nm) > 0.1 and > 0.15, respectively, from all instruments were created. Table 2 summarizes the frequency of occurrence of AOD(500nm) > 0.1 and > 0.15, respectively, in the spring (March-May) and summer (June-August) period for the four main instruments. It confirms the similarity between the Ny-Ålesund PFR and Hornsund Cimel data sets on an annual basis, while there are obviously differences between the two collocated datasets in Ny-Ålesund (PFR, SP1A) with respect to treating data with elevated AOD values. It will be interesting to follow the comparison between the PFR and the Cimel in Ny-Ålesund with respect to their agreement on such measurements in the years to come.

Table 2: Winter/spring and summer statistics of medium- and high-AOD events for all instruments and all years: upper table for AOD(500 nm) > 0.1 (years with more than 30% occasions per season: high-lighted yellow, >50%: orange, >70%: red); lower table for AOD(500 nm) > 0.15 (years with >10% occasions: yellow, >20%: orange, >30%: red). Grey: contaminated data.

Year	# of hours in season	hourly means MAM PFR	AOD500 > 0.10 MAM PFR	% high-AOD MAM PFR	hourly means MAM SP1A	AOD500 > 0.10 MAM SP1A	% high-AOD MAM SP1A	hourly means MAM CIMNA	AOD500 > 0.10 MAM CIMNA	% high-AOD MAM CIMNA	hourly means MAM CIMHS	AOD500 > 0.10 MAM CIMHS	% high-AOD MAM CIMHS
2002	2208	375	116	30.9	0	0	0	0	0	0	0	0	0
2003	2208	271	155	57.2	25	1	4	0	0	0	0	0	0
2004	2208	260	133	51.2	136	27	19.9	0	0	0	1	1	100
2005	2208	329	161	48.9	99	26	26.3	0	0	0	147	53	36.1
2006	2208	174	147	84.5	91	38	41.8	0	0	0	205	155	75.6
2007	2208	261	64	24.5	133	22	16.5	0	0	0	267	88	33.0
2008	2208	460	373	81.1	170	140	82.4	0	0	0	364	304	83.5
2009	2208	147	115	78.2	287	176	61.3	0	0	0	223	177	79.4
2010	2208	427	129	30.2	314	6	1.9	0	0	0	270	135	50.0
2011	2208	18	5	27.8	238	10	4.2	0	0	0	232	85	36.6
2012	2208	508	283	55.7	397	61	15.4	0	0	0	299	134	44.8
2013	2208	497	188	37.8	269	33	12.3	0	0	0	262	126	48.1
2014	2208	243	61	25.1	106	15	14.2	0	0	0	261	89	34.1
2015	2208	424	110	25.9	351	70	19.9	0	0	0	16	0	0.0
2016	2208	335	50	14.9	378	32	8.5	0	0	0	0	0	0.0
2017	2208	299	45	15.1	483	18	3.7	0	0	0	0	0	0.0
2018	2208	183	17	9.3	322	6	1.9	274	28	10.2	40	12	30.0
2019	2208	369	34	9.2	367	124	33.8	339	26	7.7	180	42	23.3
2020	2208	137	5	3.6	334	33	9.9	368	76	20.7	32	8	25.0

Year	hourly means JJA PFR	AOD500 > 0.10 JJA PFR	% high-AOD JJA PFR	hourly means JJA SP1A	AOD500 > 0.10 JJA SP1A	% high-AOD JJA SP1A	hourly means JJA CIMNA	AOD500 > 0.10 JJA CIMNA	% high-AOD JJA CIMNA	hourly means JJA CIMHS	AOD500 > 0.10 JJA CIMHS	% high-AOD JJA CIMHS
2002	438	30	6.8	0	0	0	0	0	0	0	0	0
2003	334	38	11.4	4	4	100	0	0	0	0	0	0
2004	313	76	24.3	126	41	32.5	0	0	0	0	0	0
2005	255	8	3.1	56	0	0.0	0	0	0	177	3	1.7
2006	154	12	7.8	88	0	0.0	0	0	0	111	2	1.8
2007	408	29	7.1	234	14	6.0	0	0	0	155	122	78.7
2008	344	31	9.0	290	5	1.7	0	0	0	339	62	18.3
2009	432	196	45.4	366	144	39.3	0	0	0	269	76	28.3
2010	193	3	1.6	317	0	0.0	0	0	0	4	1	25.0
2011	173	21	12.1	537	49	9.1	0	0	0	308	102	33.1
2012	383	41	10.7	369	11	3.0	0	0	0	199	22	11.1
2013	307	20	6.5	249	3	1.2	0	0	0	148	17	11.5
2014	340	67	19.7	376	30	8.0	0	0	0	251	32	12.7
2015	486	98	20.2	494	109	22.1	0	0	0	246	93	37.8
2016	391	30	7.7	463	32	6.9	0	0	0	171	10	5.8
2017	387	9	2.3	371	1	0.3	278	5	1.8	162	21	13.0
2018	315	26	8.3	335	27	8.1	263	27	10.3	174	39	22.4
2019	433	259	59.8	166	6	3.6	34	1	2.9	377	155	41.1
2020	0	0	0.0	465	48	10.3	445	78	17.5	298	23	7.7

Year	# of hours in season	hourly means MAM PFR	AOD500 > 0.15 MAM PFR	% high-AOD MAM PFR	hourly means MAM SP1A	AOD500 > 0.15 MAM SP1A	% high-AOD MAM SP1A	hourly means MAM CIMNA	AOD500 > 0.15 MAM CIMNA	% high-AOD MAM CIMNA	hourly means MAM CIMHS	AOD500 > 0.15 MAM CIMHS	% high-AOD MAM CIMHS
2002	2208	375	2	0.5	0	0	0	0	0	0	0	0	0
2003	2208	271	69	25.5	25	0	0	0	0	0	0	0	0
2004	2208	260	11	4.2	136	0	0	0	0	0	1	0	0
2005	2208	329	29	8.8	99	10	10.1	0	0	0	147	20	13.6
2006	2208	174	63	36.2	91	16	17.6	0	0	0	205	79	38.5
2007	2208	261	14	5.4	133	2	1.5	0	0	0	267	23	8.6
2008	2208	460	138	30.0	170	36	21.2	0	0	0	364	100	27.5
2009	2208	147	39	26.5	287	46	16.0	0	0	0	223	71	31.8
2010	2208	427	61	14.3	314	0	0.0	0	0	0	270	45	16.7
2011	2208	18	0	0.0	238	0	0.0	0	0	0	232	23	9.9
2012	2208	508	87	17.1	397	0	0.0	0	0	0	299	25	8.4
2013	2208	497	75	15.1	270	0	0.0	0	0	0	262	42	16.0
2014	2208	243	4	1.6	106	0	0.0	0	0	0	261	23	8.8
2015	2208	424	35	8.3	351	1	0.3	0	0	0	16	0	0.0
2016	2208	335	10	3.0	378	4	1.1	0	0	0	0	0	0.0
2017	2208	299	14	4.7	483	3	0.6	0	0	0	0	0	0.0
2018	2208	183	4	2.2	322	0	0.0	274	9	3.3	40	6	15.0
2019	2208	369	2	0.5	367	47	12.8	339	8	2.4	180	19	10.6
2020	2208	0	0	0.0	334	8	2.4	368	37	10.1	32	3	9.4

Year	hourly means JJA PFR	AOD500 > 0.15 JJA PFR	% high-AOD JJA PFR	hourly means JJA SP1A	AOD500 > 0.15 JJA SP1A	% high-AOD JJA SP1A	hourly means JJA CIMNA	AOD500 > 0.15 JJA CIMNA	% high-AOD JJA CIMNA	hourly means JJA CIMHS	AOD500 > 0.15 JJA CIMHS	% high-AOD JJA CIMHS
2002	438	11	2.5	0	0	0	0	0	0	0	0	0
2003	358	7	2.0	4	1	25	0	0	0	0	0	0
2004	313	24	7.7	126	15	11.9	0	0	0	0	0	0
2005	255	0	0.0	56	0	0.0	0	0	0	177	2	1.1
2006	141	0	0.0	88	0	0.0	0	0	0	111	0	0
2007	408	1	0.2	234	0	0.0	0	0	0	155	88	56.8
2008	344	3	0.9	290	0	0.0	0	0	0	339	16	4.7
2009	432	48	11.1	366	5	1.4	0	0	0	269	12	4.5
2010	193	0	0.0	317	0	0.0	0	0	0	4	1	25.0
2011	173	3	1.7	537	1	0.2	0	0	0	308	18	5.8
2012	383	3	0.8	369	0	0.0	0	0	0	199	1	0.5
2013	307	8	2.6	251	1	0.4	0	0	0	148	2	1.4
2014	340	13	3.8	377	1	0.3	0	0	0	251	17	6.8
2015	486	40	8.2	494	55	11.1	0	0	0	246	53	21.5
2016	391	6	1.5	463	6	1.3	0	0	0	171	5	2.9
2017	387	2	0.5	371	0	0.0	278	4	1.4	162	12	7.4
2018	315	14	4.4	335	15	4.5	263	16	6.1	174	17	9.8
2019	433	204	47.1	166	4	2.4	34	0	0	377	109	28.9
2020	0	0	0.0	466	32	6.9	445	48	10.8	298	16	5.4

The above-mentioned data files were used by the CNR research group to further analyse the data in relation to in-situ measurements at Gruvebadet Observatory. The initially random selection of the high-AOD values (0.1; 0.15) was confirmed by the analysis of hourly data of the Cimel instrument in Ny-Ålesund for the 2017-2020 period after application of the high AOD events detection method proposed by Mateos et al. (2020).

Table 3: Mean, minimum and maximum hourly AOD (500 nm) values for high, moderate and extreme AOD events.

	Mean	Min	Max
High AOD	**0.144**	**0.065**	**0.585**
Moderate AOD	**0.101**	**0.065**	**0.149**
Extreme AOD	**0.237**	**0.152**	**0.585**

This method uses the values of the 85th percentiles for the fine and coarse AOD (500 nm) data sets (offered by AERONET after applying the spectral deconvolution algorithm, SDA) as thresholds. For the days detected as high-level events (High AOD) with the method, the minimum, maximum and mean hourly values of AOD at 500 nm have been calculated. As an additional step, we distinguished between moderate (AOD_500nm < 0.15) and extreme (AOD_500nm > 0.15) episodes. Results are summarized in Table 3.

To investigate the link between high-AOD episodes and aerosol optical properties observed at the ground, the boxplot in figure 5 shows the statistical distribution of extinction, absorption, and scattering coefficients measured at about sea level (Gruvebadet observatory) when AOD recorded at Ny-Ålesund was larger than 0.15 (extreme AOD), between 0.15 and 0.1 (moderate AOD), and below 0.1 (low AOD). Statistically significant higher extinction, absorption, and scattering coefficients are observed during high AOD episodes (95% confidence level). Classification is based on AOD data from Cimel, SP1A, and PFR at Ny-Ålesund. PFR data between July 9 – August 28, 2019, were excluded from the analysis, because in this period with practically continuous high-AOD conditions there were no Cimel and SP1A data available, while the number of high-AOD values from the PFR was so large that it caused a severe bias in the 10-year data record. Preliminary analysis also revealed that aerosols during this episode were different from the other high-AOD events and deserve an in-depth analysis.

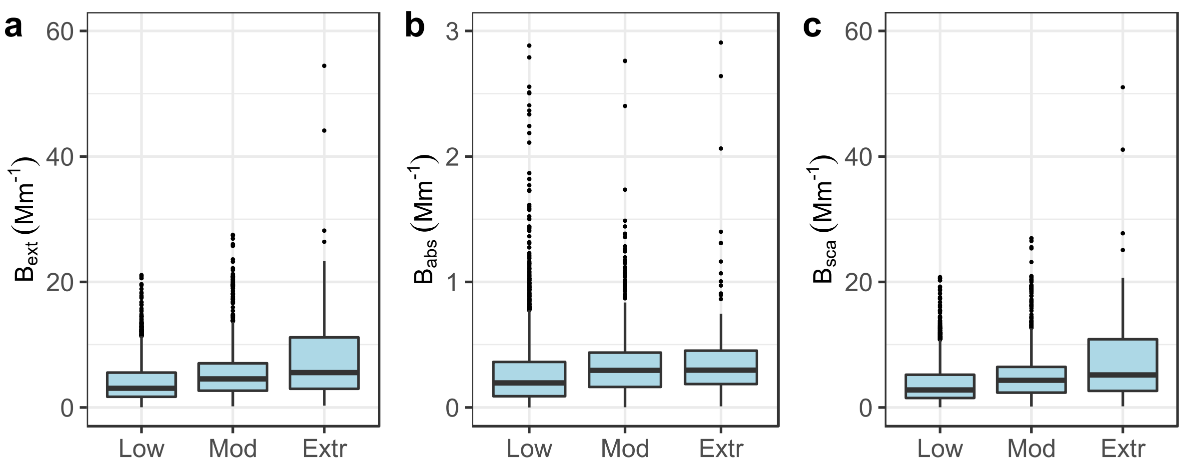

Figure 5: Box-whisker plot of extinction (panel a), absorption (panel b), and scattering coefficients (panel c) at 530 nm measured at the Gruvebadet observatory during low, moderate, and high AOD episodes in Ny-Ålesund, from 2010 to 2020.

Following up, we identified high-aerosol-load episodes from ground-based/in-situ measurements and compared with high-AOD events (moderate and extreme). We first applied a Kolmogorow-Zurbenko filter to the extinction coefficient time series (180-day length and 3 iterations) to remove the seasonal variability. Events characterized by de-seasonalized extinction coefficient higher than 3 times the standard deviation of the running average are then identified as high aerosol episodes. Table 4 shows that 65, 60, and 35 hours are identified as high aerosol loading episodes by both ground measurements and PFR, SP1A, and Cimel observations, respectively. About 10% of high AOD events are not observed at the ground (low extinction coefficient and high AOD cases), indicating aerosol layer at higher altitudes.

A few high extinction coefficient episodes (about 1% of the events) are not recognized as high AOD episodes. Such cases are characterized by slightly lower average extinction coefficients compared to the high extinction / high AOD cases, and can be linked to local contamination or shallow boundary layer.

Table 4: Confusion matrices of extinction coefficient and AOD for PFR (a), SP1A (b), and Cimel (c) observations. Average extinction coefficients (Ext in Mm-1) is reported between brackets.

PFR	**High Ext**	**Low Ext**
High AOD	65 (Ext 20.0)	461 (Ext 5.2)
Low AOD	41 (Ext 12.0)	3257 (Ext 4.1)

SP1A	**High Ext**	**Low Ext**
High AOD	60 (Ext 21.6)	316 (Ext 4.8)
Low AOD	38 (Ext 15.2)	4108 (Ext 4.0)

Cimel	**High Ext**	**Low Ext**
High AOD	35 (Ext 19.4)	122 (Ext 4.6)
Low AOD	15 (Ext 15.6)	1232 (Ext 4.1)

5 Black Carbon measurements at Ny-Ålesund and their relation to AOD measurements

In Ny-Ålesund black carbon is an agent of choice to connect in-situ aerosol observations with remote sensing observations such as sun photometers yielding AOD. BC measurements have been performed there since the 1990s, but all the time from the Zeppelin Observatory at 475 m a.s.l., while AOD and in-situ observations are made approximately at sea level. Previous studies of aerosol absorption at the two levels have shown that they are mostly in the same layer during summer months but can be decoupled during winter, which means that the boundary layer in winter often extends to less than 475 m.

The effect of atmospheric dynamics at regional or local scale and their effect on the vertical profile of aerosol metrics can be studies at Ny Aalesund observing the variability of a parameter like the aerosol absorption coefficient (b_{abs}) measured in-situ at two altitudes at the Gruvebadet observatory (30 m asl) and the Zeppelin Observatory (475 masl).

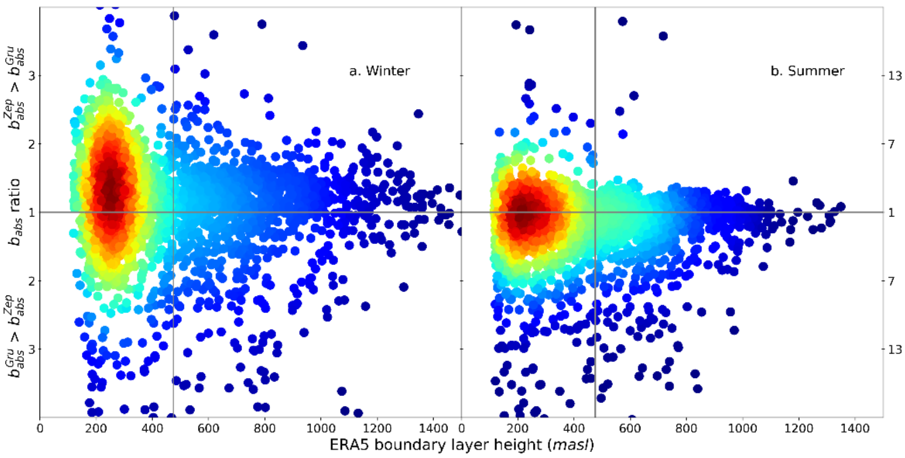

Figure 6: Scatter plot between the ratio of hourly b_{abs} and ERA5 for winter (a) and summer (b) periods. The color represents the kernel density of the axis pair

A first comparison was attempted combining the data from the two observatories obtained by parallel measurements during a two year period 2017-2018 with respect to the calculated Boundary layer height by the ERA 5 model. The ratio of aerosol absorption between the two sites (r) is the criterion in order to explore the relationship between sites. r_{zep} is the ratio between the two sites and includes the hourly values b_{abs} when the Zeppelin value is higher than Gruvebadet and r_{gru} are the pairs of data when the value at Gruvebadet is greater than the one at Zeppelin Observatory.

We observe that the ratio between the absorption values observed at the two sites are centered around unity in the summer, while during winter the frequency of data where the aerosol absorption coefficient is higher at Zeppelin is somewhat higher. However, in order to classify these findings as significant a larger dataset needs to be employed for this comparison.

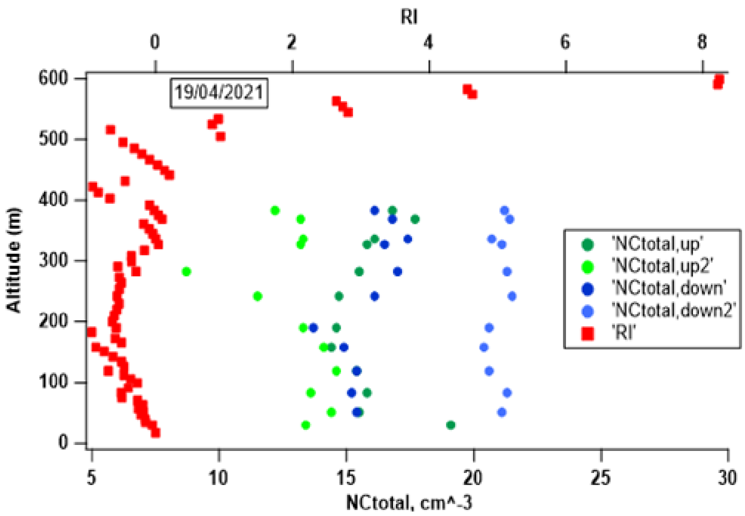

Figure 7: Profiles of aerosol particle number measurements during "cable car campaign" with altitude dependent atmospheric stability conditions (Ri < 0.25 below 500 m, Ri > 0.25 above), derived from radiosonde launch at AWIPEV Station.

One activity of Rehearsol was to probe the whole altitude range in order to obtain new in-situ data with respect to aerosol concentration levels . This was conducted during the ReHearsol project in a field campaign by operating portable aerosol absorption and particle counting monitoring instruments on the cable car during its daily routine trips to the mountain station.

The dataset was combined with data from daily radiosondes launched from the AWIPEV Observatory used to calculate Richardson number profiles. The short campaign took place in April 2021 and resulted in a number of BC absorption profiles and size resolved particle number concentrations. While the analysis of these measurements is still ongoing, a preliminary conclusion is that in most cases during this late winter period, the two stations are both in the boundary layer, but in some cases they are clearly decoupled with aerosol concentrations varying by up to 50%. Figure 7 shows one example of the particle measurements onboard the Zeppelin mountain cable car combined with ancillary measurements of atmospheric stability.

6 Data Handling

All level-2 data available from the above-listed instruments have been collected at the project platform. Annual files in 1-minute resolution containing AOD at 4 wavelengths (SP1A: 5 wavelengths) and the resulting Ångström exponent have been produced; for the marine measurements, also geographical coordinates for each measurement are included in the annual high-resolution files. The annual files have been submitted to the SIOS Knowledge Centre which will transform them into the standard format of the SIOS Data Management System (Net-CDF).

The files will be preserved through the Arctic Data Centre hosted by the Norwegian Meteorological Institute and be available as an independent SIOS data set. At the time of completion of this report (February 2022), the practical implementation of this process is ongoing; as an example the 2020 data file start is shown in figure 8. In addition, separate single instrument data sets (sun and moon data from PFR and Cimel instruments) are available through different databases (EBAS: https://ebas.nilu.no; AERONET: https://aeronet.gsfc.nasa.gov/).

```
High-resolution data of AOD(4 (SP1A: 5) wavelengths) and AE (all-wavelength fit)
PFR Sverdrup Station (PMOD/NILU)
78.923257 N, 11.929357 E
PIs: N. Kouremeti (Natalia.Kouremeti@pmodwrc.ch) & S. Kazadzis (Stelios.Kazadzis@pmodwrc.ch) (PMOD)/ G.
Hansen (ghh@nilu.no) (NILU)
SP1A AWIPEV Station (AWI)
78.923181 N, 11.922232 E
PI: C. Ritter (Christoph.Ritter@awi.de) (AWI)
Cimel AWIPEV Station (AWI/UVa)
78.923181 N, 11.922232 E
PIs: D. Mateos (mateos@goa.uva.es) (UVa-GOA); C. Ritter (Christoph.Ritter@awi.de) (AWI)
Cimel Hornsund Station (IGFPAS/UVa)
77.001579 N, 15.541997 E
PIs: P. Sobolewski (pss@ra.onet.pl) (IGFPAS); D. Mateos (mateos@goa.uva.es) (UVa-GOA)
Microtops Oceania (IOPAS) North of 70 deg N
PIs: T. Zielinski (tymon@iopan.pl) & Paulina Pakszys (pakszys@iopan.pl) (IOPAS)
Microtops Polarstern (TROPOS/AWI/IOPAS) North of 70 deg N
PI: D. Althausen (dietrich@tropos.de) (TROPOS)

Parameters:
Year
Month
Day
DoY[decimal day]
AOD(368 nm) - PFR [Missing value, MV: -9.9999]
AOD(412 nm) - PFR [MV: -9.9999]
AOD(500 nm) - PFR [MV: -9.9999]
AOD(862 nm) - PFR [MV: -9.9999]
AE(4-wavelength) - PFR [MV: -9.9999]
AOD(368 nm) - SP1A AWIPEV [MV: -9.9999]
AOD(381 nm) - SP1A AWIPEV [MV: -9.9999]
AOD(412 nm) - SP1A AWIPEV [MV: -9.9999]
AOD(500 nm) - SP1A AWIPEV [MV: -9.9999]
AOD(860 nm) - SP1A AWIPEV [MV: -9.9999]
AE(4-wavelength) - SP1A AWIPEV [MV: -9.9999]
AOD(380 nm) - Cimel AWIPEV [MV: -9.9999]
AOD(440 nm) - Cimel AWIPEV [MV: -9.9999]
AOD(500 nm) - Cimel AWIPEV [MV: -9.9999]
AOD(870 nm) - Cimel AWIPEV [MV: -9.9999]
AE(4-wavelength) - Cimel AWIPEV [MV: -9.9999]
AOD(380 nm) - Cimel Hornsund [MV: -9.9999]
AOD(440 nm) - Cimel Hornsund [MV: -9.9999]
AOD(500 nm) - Cimel Hornsund [MV: -9.9999]
AOD(870 nm) - Cimel Hornsund [MV: -9.9999]
AE(4-wavelength) - Cimel Hornsund [MV: -9.9999]
Oceania Latitude [MV: -99.999]
Oceania Longitude [MV: -99.999]
AOD(440 nm) - Microtops Oceania [MV: -9.9999]
AOD(500 nm) - Microtops Oceania [MV: -9.9999]
AOD(675 nm) - Microtops Oceania [MV: -9.9999]
AOD(870 nm) - Microtops Oceania [MV: -9.9999]
AE(440,870) - Microtops Oceania [MV: -9.9999]
Polarstern Latitude [MV: -99.999]
Polarstern Longitude [MV: -99.999]
AOD(440 nm) - Microtops Polarstern [MV: -9.9999]
AOD(500 nm) - Microtops Polarstern [MV: -9.9999]
AOD(675 nm) - Microtops Polarstern [MV: -9.9999]
AOD(870 nm) - Microtops Polarstern [MV: -9.9999]
AE(440,870) - Microtops Polarstern [MV: -9.9999]
AOD(412 nm) - lunar PFR [MV: -9.9999]
AOD(500 nm) - lunar PFR [MV: -9.9999]
AOD(675 nm) - lunar PFR [MV: -9.9999]
AOD(862 nm) - lunar PFR [MV: -9.9999]
AE(4-wavelength) - lunar PFR [MV: -9.9999]
AOD(440 nm) - lunar Cimel AWIPEV [MV: -9.9999]
AOD(500 nm) - lunar Cimel AWIPEV [MV: -9.9999]
AOD(675 nm) - lunar Cimel AWIPEV [MV: -9.9999]
AOD(870 nm) - lunar Cimel AWIPEV [MV: -9.9999]
AE(4-wavelength) - lunar Cimel AWIPEV [MV: -9.9999]

YYYY   MM   DD  DoY       PFR:AOD368 AOD412  AOD500  AOD862 AE(4-wl) SP1A:AOD368 AOD381 AOD412 AOD500
AOD860 AE(4-wl) CMNA:AOD380 AOD440 AOD500 AOD700 AE(4-wl) CMHS:AOD380 AOD440 AOD500 AOD700 AE(4-wl)
MAN-Oc:lat lon AOD440 AOD500 AOD675 AOD870 AE(440,870) MAN-Ps:lat lon AOD440 AOD500 AOD675 AOD870
AE(440,870) lunar PFR:AOD412 AOD500  AOD675  AOD862 lunar Cimel:AOD440 AOD500  AOD675  AOD870
------------------------------------------------------------------------------------------------------
2020    2    1  32.86736111  -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
-9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999
-99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999  -99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
0.0000  0.0650  0.0250  0.0240  1.9110 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
2020    2    1  32.86805556  -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
-9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999
-99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999  -99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
0.0000  0.0630  0.0280  0.0240  1.8150 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
2020    2    1  32.87013889  -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
-9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999
-99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999  -99.999  -99.999 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
0.0000  0.0660  0.0290  0.0240  1.8720 -9.9999 -9.9999 -9.9999 -9.9999 -9.9999
```

Figure 8: Header and first data lines of 2020 high-resolution data file.

7 Future perspectives for a Svalbard AOD network

In the frame of the ReHearsol project, all available AOD-data (and derived products) from the Svalbard region from 2002 to 2020 have been collected and combined into annual files. All technical tools needed to continue this practice for future years are now in place. Thus, new data can now easily be digested into the system as soon as they become available on their respective networks, and can be provided to the SDMS for further use in the SIOS network and beyond.

The aim to establish one homogenized AOD data-series for the whole of Svalbard has proven not to be meaningful as there is substantial geophysical variation between aerosol conditions at the different sites and as there is insufficient agreement between two of the three AOD data-series at Ny-Ålesund. However, with a Cimel and a GAW-PFR instrument in operation simultaneously at Ny-Ålesund in the future, both being quality-controlled, calibrated in their respective networks, and inter-compared, there is a large probability to cover all (weather-conditioned) opportunities for AOD-measurements. The availability of two independent instruments at Ny-Ålesund also opens up for the option to further develop the spectral AOD derivation capacity of the recently established Pandora spectrometer as a new element in the SIOS infrastructure. The results of this project, including an extension with 2021 data and additional investigations, will hopefully be published through the next "State of Environmental Science in Svalbard" report (SESS 2022), and further publications based on ReHearsol data are already published or underway (e.g., Zbizika et al., 2022).

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9 Environmental Impact of the Project

The ReHearsol project was mostly performed online. The only field activity, altitude-dependent black carbon measurements at the Zeppelin Mountain cable car, were performed in connection with regular maintenance visits to the Zeppelin Observatory. All project meetings were arranged virtually. The project thus had no (additional) environmental impact at all.

10 Contribution to Relevant SSF Priorities

The ReHearsol project has contributed to two major activities supported by SSF:

- the Atmospheric Svalbard flagship project;
- the SIOS project.

With respect to the flagship project, ReHearsol has put the extension from Ny-Ålesund to Svalbard as a whole into practice, by integrating the AOD-monitoring instruments from Hornsund and marine observations into the Ny-Ålesund network. With respect to SIOS, ReHearsol has gathered all AOD measurements in Svalbard since 2002, inter-compared them, and gathered all data which are applicable to other fields of research covered by SIOS. All the data are made available through the SIOS Data Management System.

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