

A Satellite view on Aerosols in the Arctic: climatology, fire, and dust (SVAR)

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WP3: Arctic dust aerosol

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Contents

1	Introduction	5
2	Data	6
2.1	Aerosol models	6
2.2	Satellite data	7
2.2.1	Sea and Land Surface Temperature Radiometer	7
2.2.2	Infrared Atmospheric Sounding Interferometer	7
2.3	Surface in-situ data	8
3	Methods	8
3.1	CAMS and FLEXDUST extreme events screening	8
3.2	SLSTR aerosol detection	9
3.3	Analysis of the in-situ filter observations	11
4	Results	13
4.1	Northern Europe October 2020 event	14
4.2	Dust over Russia	18
4.2.1	SLSTR data 8 May 2020	19
4.2.2	SLSTR data 14 April 2021	22
4.3	Surface dust episodes in Ny-Ålesund	26
4.3.1	Top 10 strongest in-situ episodes	26
4.3.2	IASI data 13 May 2019	27
4.3.3	IASI data 2 November 2020	27
4.3.4	SLSTR data 2 November 2020	28
5	Discussion	28
A	Extreme dust events in the CAMS data	33
B	TROPOMI/S-5P PAL AOD, SLSTR/OCLI/S-3 SYNERGY AOD and CALIOP/CALIPSO data for 14 April 2021	35
C	SLSTR AOD product 2018-2021	39

Preamble

This report describes the work done within SVAR WP3 by NILU.

1 Introduction

The objective of SVAR WP3 is

“to characterize dust aerosol episodes in the European Arctic, which are identified by in situ observations on Svalbard, satellite, or by Copernicus Atmosphere Monitoring Service (CAMS), based on multiple-instrument satellite information and in situ observations.”

A recent NILU study finds evidence that mineral dust (Mn, Cr, Ni) is increasing at the Zeppelin Observatory in Svalbard (Platt et al., 2022). Bowen and Vincent (2021) showed an increase in the spatial extent of dust at both poles, based on satellite thermal data. Given that both local and remote coarse-mode particle sources in the Arctic are limited, there is an ongoing debate whether observations are caused by change in atmospheric air mass advection patterns, enhancement in sea spray due to reduced sea ice cover, or regional and/or long-range transport of dust. Atmospheric dust in the Arctic consists of long-range transported dust, as well as dust from local sources, with the latter being more important than previously thought (Groot Zwaaftink et al., 2016; Schmale et al., 2022). Heslin-Rees et al. (2020) interpreted the increase of the concentration of coarse mode aerosol at Zeppelin, Svalbard, based on in situ observation of optical properties, as a change in atmospheric air mass advection patterns (i.e., not linked to sea ice retreat). Improved knowledge of the radiative impacts of dust is needed to assess its role in the Arctic Amplification (see for example Kylling et al., 2018).

To study mineral dust aerosol episodes in the Arctic we use three complementary methods:

1. Identification of dust episodes using CAMS and FLEXDUST model data.
2. Investigation of dust episodes using SLSTR data and the brightness temperature difference method.
3. Analysis of in-situ observations in Svalbard.

The CAMS global reanalysis data¹ (ECMWF Atmospheric Composition Reanalysis (EAC4), Inness et al., 2019) are used to investigate how various dust aerosol types are transported into the Arctic and to identify extreme dust episodes. In addition we also use the dust data from the FLEXDUST model (Groot Zwaaftink et al., 2016). Both data sets will allow us to trace the origin of the dust events and thus identify the most prominent source regions for mineral dust in the Arctic.

The Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3A and Sentinel-3B satellites includes measurements of the brightness temperatures BT_{11} and BT_{12} centred at around 11 and 12 μm respectively. The brightness temperature difference, $dB T_{11-12}$, is positive for snow and ice, slightly positive for water, and negative for sand or mineral dust. As Bowen and Vincent (2021) we use $dB T_{11-12}$ to identify mineral dust episodes in the Arctic. The use of brightness temperatures for this purpose allows mineral dust episodes to be detected independently of season and day/night. Volcanic ash eruptions also produce a negative $dB T_{11-12}$. Such events data may be removed from the analysis using knowledge about eruption height and transport as available from operational in-house dispersion modelling and SEVIRI, CALIOP, and IASI analysis.

Finally, in-situ data at the Zeppelin observatory (78.93°N, 11.92°E, 474 m above sea level) will be scrutinized for the presence of mineral dust from weekly filter samples (heavy metals are measured twice a week) particle number size distributions, from the aerodynamic particle sizer (APS) instrument (from 2021 onwards), and photometer observations downtown in Ny-Ålesund (for details see e.g. Myhre et al., 2021). The Ny-Ålesund/Zepplin data only represent one location, but they can give an indication on the origin of the dust and its composition.

The information from the three methods will together provide insight into the frequency, magnitude, and origin of airborne mineral dust in the Arctic.

¹<https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4>

2 Data

2.1 Aerosol models

The CAMS aerosol data were taken from the Copernicus Atmosphere Monitoring Service reanalysis (CAMSRA, [Inness et al., 2019](#)). The CAMSRA aerosol model ([Inness et al., 2019](#))

“is a hybrid bulk–bin scheme with 12 prognostic tracers, consisting of three bins for sea salt depending on size (0.03–0.5, 0.5–5 and 5–20 μm), three bins for dust (0.030–0.55, 0.55–0.9 and 0.9–20 μm), hydrophilic and hydrophobic organic matter (OM), and black carbon (BC), plus sulfate aerosol and a gas-phase sulfur dioxide (SO_2) precursor. The different aerosol types are treated as externally mixed, i.e. separate particles. Transport by advection, convection and diffusion is handled by the meteorological model component of the IFS. The aerosol scheme includes prescribed and online emissions, dry and wet deposition, production of sulfate from SO_2 , and ageing of hydrophobic OM and BC to hydrophilic OM and BC.”

The CAMSRA aerosol data includes the total, black carbon, dust, organic matter, sea salt and sulphate aerosol optical depths. The horizontal resolution is $0.75^\circ \times 0.75^\circ$ and the temporal resolution 3 hours. An example of CAMSRA aerosol optical depths is shown in Fig. 1.

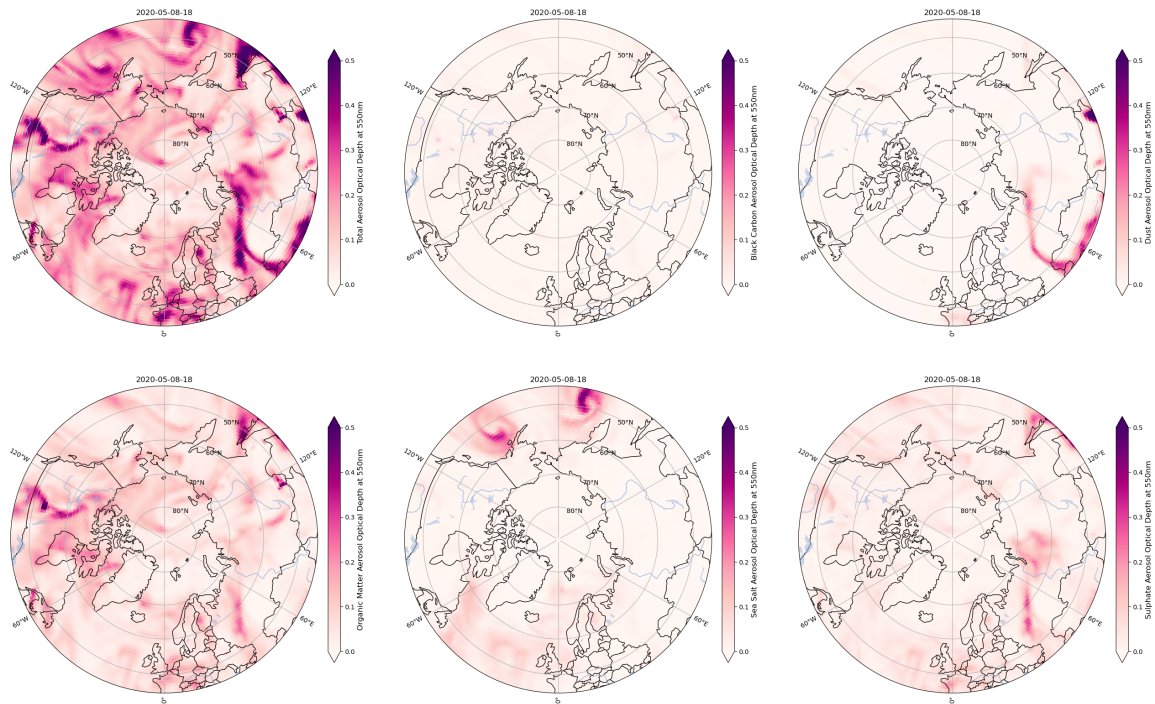


Figure 1: Aerosol optical depth from CAMS reanalysis for 8 May 2020, 18:00. The total, black carbon, dust, organic matter, sea salt and sulphate aerosol depth is shown from top left to bottom right.

Another source of dust is the FLEXDUST data set which includes globally daily dust profiles at $1^\circ \times 1^\circ$ resolution ([Groot Zwaafink et al., 2016](#)). This data set includes dust sources at high latitudes as shown in Fig 2. These are often missing in other models. However, as shown in Fig. 7 of [Groot Zwaafink et al. \(2016\)](#) the largest sources to dust loads in the Arctic are in Africa and Asia south of 60°N .

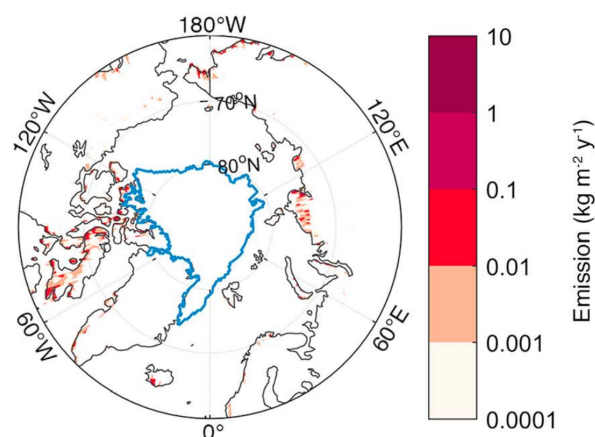


Figure 2: Simulated Arctic annual mean dust emissions. Adopted from [Groot Zwaafink et al. \(2016\)](#).

2.2 Satellite data

2.2.1 Sea and Land Surface Temperature Radiometer

The first Sentinel-3 satellite (S3A) ([Donlon et al., 2012](#)) was launched 16 February 2016 and the second (S3B) on 25 April 2018. The Ocean and Land Colour Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR) are part of the payload of the S3 mission. The payload also includes a microwave radiometer and a radar altimeter. Some relevant characteristics for SLSTR used in this study, are provided below.

SLSTR consists of two identical instruments, one looking in the nadir direction and the other in the backward direction. The oblique view swath is about 740 km while the nadir view swath is about 1,400 km. Detailed SLSTR information is available at <https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-slstr>.

2.2.2 Infrared Atmospheric Sounding Interferometer

METOP-A, jointly established by the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), was the first in a series of three European polar-orbiting meteorological satellites. It was launched on October 19, 2006 (retired 30 November 2021). Metop-B was launched on 17 September 2012, and Metop-C was launched on 7 November 2018. The payload of the METOP-satellites include a suite of instruments dedicated to meteorological observations and scientific measurements. The Infrared Atmospheric Sounding Interferometer (IASI) instrument provides temperature and water vapour profiles in the troposphere and the lower stratosphere, as well as measure quantities of ozone, carbon monoxide, methane and other compounds.

Here, we utilized the IASI LMD (Laboratoire de Météorologie Dynamique) mineral dust AOD product from METOP-A and METOP-C. The data are downloaded from the C3S Climate Data Store (CDS²). The main product is dust-AOD at 10 μm . In addition, dust-AOD at 0.55 μm is provided, using priori knowledge of the aerosol microphysical properties (size distribution, effective radius, refractive index), using a Lorenz–Mie calculation, for the conversion. For details see https://wdc.dlr.de/C3S_312b_Lot2/Documentation/AER/C3S_2_312a_Lot2_ATBD_AER_F_latest.pdf, and references therein.

²<https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-aerosol-properties>

2.3 Surface in-situ data

The ground-based surface point in-situ data used in this work originates from various measurements taken at the Zeppelin Observatory (78.93°N, 11.92°E, 474 m above sea level) in Ny-Ålesund, Svalbard, Norway, as part of the European Monitoring and Evaluation Programme (EMEP) and the Aerosol, Cloud and Trace Gas Research Infrastructure (ACTRIS). Data are available in the EBAS database <https://ebas-data.nilu.no/>.

The study is based on observations of Al, Fe, Ti, Mn (mineral dust elements) and As and Pb (anthropogenic elements; positive control that not all correlates due to meteorology). Data from 2018-2021 (4 years) were studied. The sampling frequency is 48 hours (filters) and subsequent element analysis using Inductively coupled plasma mass spectrometry (ICP-MS), which is the reference technique within EMEP, was performed. The data were quality assured; invalid measurements were removed.

3 Methods

3.1 CAMS and FLEXDUST extreme events screening

For the CAMS data extreme dust AOD events were identified as those with AOD larger than the 95 percentile value of the total AOD. The 95 percentile was also used by [Xian et al. \(2022a\)](#) to identify extreme AOD events. Furthermore, it was required that at least 10 pixels for a single time step should be above the 95 percentile value. The CAMS 95 percentile value, AOD_{95} , varies between 0.18-0.25 for the years 2018-2021. The average is 0.21 and this was used as the 95 percentile value.

The FLEXDUST data includes dust particle concentrations in various size ranges. The total dust loading in a column was obtained by summing all size bins and integrating over altitude. The optical depth (CAMS) and the column loading (FLEXDUST) are not directly comparable quantities. By experimenting with various percentile values, extreme events in the FLEXDUST data set were identified as those where the column loading was larger than the 99 percentile value. In addition, it was required that at least 10 pixels for a single time step should be above the 99 percentile value.

For both data sets an extreme event was identified if more than 10 pixels in a single image are above the percentile value. All these pixels are included in the further analysis. Typically the FLEXDUST events include more pixels (events are larger in size) than the CAMSRA data, see for example Fig. 3. Thus, in the plots below, more extreme event pixels are present for the FLEXDUST data compared to the CAMSRA data.

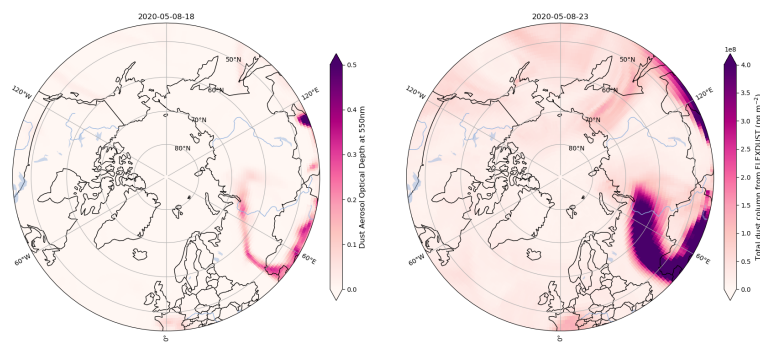


Figure 3: (left) Dust aerosol optical depth from CAMS reanalysis for 8 May 2020, 18:00. (right) Dust column amount from FLEXDUST for 8 May 2020.

Also note that the results from the two data sets are not directly comparable. Although the FLEXDUST data has been analyzed similar to the CAMS, CAMS provides dust optical depths and FLEXDUST gives dust particle concentrations in various size ranges.

3.2 SLSTR aerosol detection

The radiometric bands of SLSTR are presented in Table 1.

Table 1: Characteristics of the radiometric bands of SLSTR. Note that the F1 and F2 fire bands are based on the same detectors as S7 and S8 but with an increased dynamic range to prevent saturation over fires. Adopted from <https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-slstr/resolutions/radiometric>.

Band	λ centre (μm)	Width (μm)	Function	Comments		Res. (m)
S1	0.555	0.02	Cloud screening, vegetation monitoring, aerosol	Visible Near IR	Solar reflectance bands	500
S2	0.659	0.02	NDVI, vegetation monitoring, aerosol			
S3	0.865	0.02	NDVI, cloud flagging, Pixel co-registration			
S4	1.375	0.015	Cirrus detection over land	Short-Wave IR		
S5	1.61	0.06	Cloud clearing, ice, snow, vegetation monitoring			
S6	2.25	0.05	Vegetation state and cloud clearing			
S7	3.74	0.38	SST, LST, Active fire	Thermal infra-red Ambient bands (200 K - 320 K)		1000
S8	10.85	0.9	SST, LST, Active fire			
S9	12	1	SST, LST			
F1	3.74	0.38	Active fire	Thermal infra-red fire emission bands		
F2	10.85	0.9	Active fire			

For SVAR the S8 and S9 bands are used. The spectral responses of these two bands are shown in the right plot of Fig. 4.

To detect dust the difference in brightness temperature ($dB T$) between the S8 and S9 bands is used:

$$dB T = dB T_{11-12} = I_{S8} - I_{S9} \quad (1)$$

Following Yu et al. (2002) the radiances I may be approximated by:

$$I_{S8} = e_{S8} B_{S8}(T_c) + t_{S8} e_{S8}^s B_{S8}(T_s) \quad (2)$$

$$I_{S9} = e_{S9} B_{S9}(T_c) + t_{S9} e_{S9}^s B_{S9}(T_s) \quad (3)$$

where t and e are the transmittance and emissivity of the dust layer, respectively. The Earth's surface has the temperature T_s and emissivity e^s while the dust layer is at the temperature T_c and $B(T)$ is the Planck function.

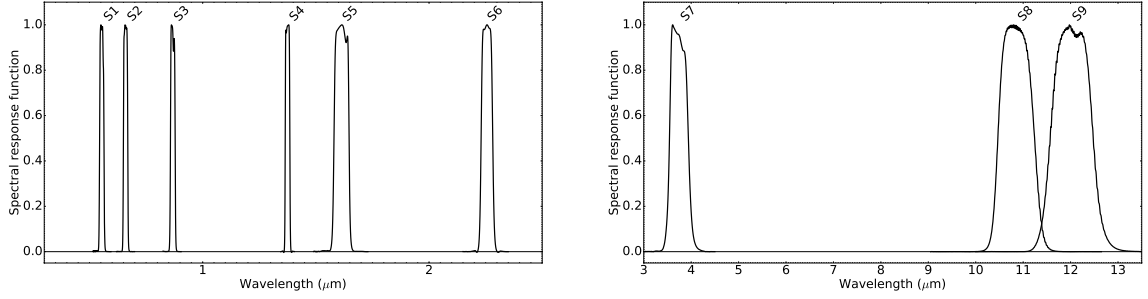


Figure 4: The spectral responses of the SLSTR solar S1-S6 bands (left plot) and thermal S7-S9 bands (right plot).

The radiation emitted from the surface depends on the emissivity, e^s , of the surface. For water surfaces this is readily available, for land surfaces the emissivity changes with surface type and may fluctuate with time.

To get a picture of how $dB T$ varies with the aerosol cloud temperature, the surface temperature and the emissivities, the approach by [Prata and Grant \(2001\)](#) is followed. They assumed that the radiances can be linearized to brightness temperatures and thus Eqs. 2-3 become:

$$I_{S8} = e_{S8}T_c + (1 - e_{S8})T_s \quad (4)$$

$$I_{S9} = e_{S9}T_c + (1 - e_{S9})T_s. \quad (5)$$

Neglecting scattering we write

$$e_i = 1 - \exp(-k_i L) \quad (6)$$

where k is the absorption coefficient and L the geometric thickness of the aerosol cloud. Reproducing [Prata and Grant \(2001\)](#) one gets:

$$dB T = I_{S8} - I_{S9} = \Delta T_c (X - X^\beta), \quad (7)$$

where

$$X = 1 - \frac{\Delta T_{S8}}{\Delta T_c} \quad (8)$$

$$\beta = \frac{k_{S9}}{k_{S8}} \quad (9)$$

$$\Delta T_{S8} = T_s - T_{S8} \quad (10)$$

$$\Delta T_c = T_s - T_c \quad (11)$$

Unless there is an inversion, generally $T_s > T_c$. For liquid water clouds k_{S9} is close to k_{S8} , and hence β is close to one and $dB T \approx 0.0$. For ice water clouds $k_{S9} > k_{S8}$, $\beta > 1$ and $dB T > 0.0$. For dust type aerosols $k_{S9} < k_{S8}$, $\beta < 1$ and $dB T < 0.0$. Thus, $dB T$ may be used to identify and discriminate various atmospheric particulates. It is noted that in the presence of strong inversions $T_s < T_c$ and the sign of $dB T$ is reversed for dust clouds.

It is noted that a SLSTR based aerosol product is available from dataspace.copernicus.eu. For the period 2018-2021 only 5 scenes with this product are available for latitudes north of about 50° . They are shown in Fig. 28. Due to the scarcity of data no further analysis is performed using this data product.

Note, that we recently obtained the internal C3S L2 METOP-A SLSTR aerosol data (SDV aerosol product from the Finnish Meteorological Institute, version 2.30, June 2017 - June 2023), as well as downloaded the Sentinel-3 OLCI/SLSTR Synergy aerosol data (ESA non-time-critical (NTC) data, February 2020 - now). The analysis of the data is ongoing (as part of SVAR WP1).

3.3 Analysis of the in-situ filter observations

The 2018-2021 time series for mineral dust elements (Al, Fe, Ti, Mn) and anthropogenic elements (As, Pb) were quality controlled and compared internally with each other to find correlative ratios. The screened data sets for each trace element for the time period 2018-2021 and their seasonality are shown in Fig. 5.

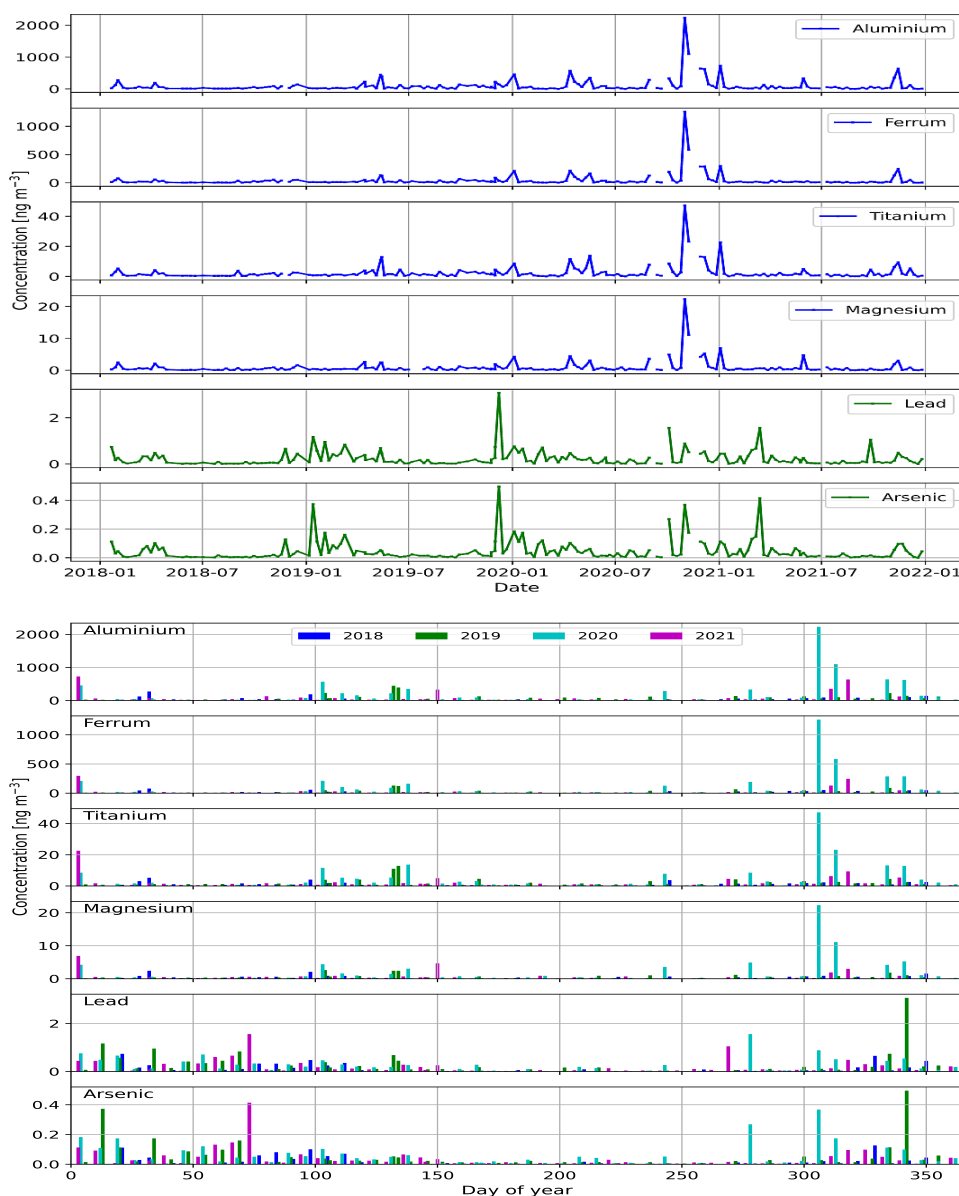


Figure 5: Time series [upper panel] and seasonality of trace elements observed at Zeppelin mountain [in ng m⁻³]

Trajectories alone are not sufficient, but can help to answer whether the emissions are Long Range Transport (LRT) or of local origin. It seems possible/plausible that there are more LRT episodes for the selected anthropogenic species compared to the mineral dust, but this needs further investigations.

At NILU, the FLEXible TRAjectory model (FLEXPART) (Pisso et al., 2019) is used for the analysis of the transport of dust (Groot Zwaafink et al., 2016) as well as for other tracers, like black carbon (BC). Albeit crude, BC is a tracer of anthropogenic activity, as is As and Pb (coal combustion, metallurgic activity, ...), thus co-variation is likely. Close to Svalbard, there are few major local sources of e.g., As and Pb, whereas there are local sources of

mineral dust. We do not see a major Arctic haze build-up of the mineral dust species, whereas this is more likely for the anthropogenic ones (see the lower panel of Fig 5 showing the seasonal variations). Groot Zwaafink et al. (2016) showed that dust deposition in the Arctic from remote sources occurs mainly in spring and local dust source are more abundant in autumn.

Here, we concentrate on the ten highest mineral dust-episodes. An analysis of the 30 years of dust data from Zeppelin mountain is ongoing (K. E. Yttri, personal communication).

The screened time series are compared to find their internal correlations, see Table 2. The ratios between Al:Fe, Al:Ti, Al:Mn, Fe:Ti, Fe:Mn, Ti:Mn are studied in-depth. Al, Fe, Ti, and Mn (mineral dust) correlates highly, as do As and Pb (anthropogenic). No correlation was found between mineral dust and the anthropogenic species.

Table 2: Correlations between mineral dust (Al, Fe, Ti, Mn) and anthropogenic elements (As, Pb).

	Fe	Ti	Mn	As	Pb
Al	0,959	0,954	0,955	0,196	0,088
Fe		0,920	0,951	0,204	0,075
Ti			0,919	0,179	0,085
Mn				0,218	0,094
As					0,828

For further analysis a ternary plot was produced (see Fig. 6). The ternary plot, also known as de Finetti diagram, shows the ratios of three variables as positions in an equilateral triangle. Each corner of the triangle represents 100 percent of one of the variables. A point inside the triangle represents the ratios of the three variables. It provides insights into the composition of mineral dust by showing the relative proportions of three selected components. In this study we have compared Al, Fe $\times$ 2 and Ti $\times$ 30.

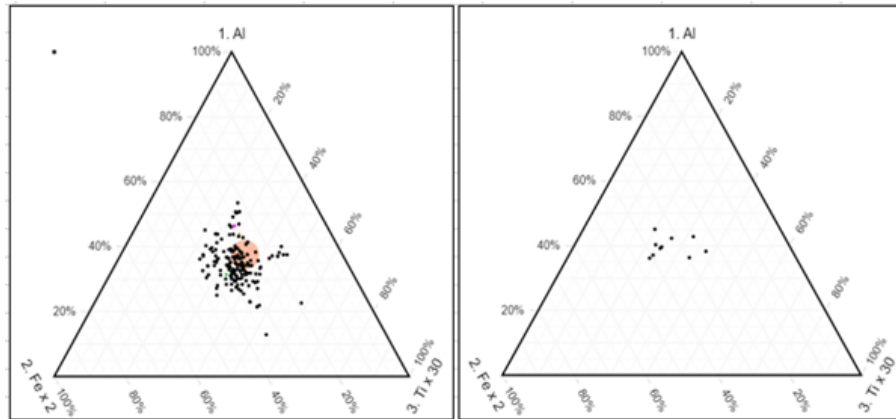


Figure 6: Ternary plot to illustrate spread in Al : Fe ($\times$ 2) : Ti ($\times$ 30) for the entire population (left panel) and the top-ten population (right panel)

To say something quantitatively of the contribution of mineral dust in the time series, we have used the following assumption: $[MD] = [SiO_2] + [Al_2O_3] + [Fe_2O_3] + [MnO] + [TiO_2]$; $[SiO_2] = 2.5 \times [Al_2O_3]$. Several formulas can be used to calculate the contribution of mineral dust in time series, and the levels obtained in this study should thus be considered an estimate.

After estimating quantitatively the contribution of mineral dust, the top-ten populations (mean) resulting from the MD-method above, are extracted from this dataset. The result is listed in Table 3.

The time period from 2 November until 11 November 2020 is remarkably high, and it seems also to be a significant episode during the period 30 November to 9 December 2020. Unfortunately, the filter samples are only for 48h one time per week, and it is thus not possible from this dataset alone to study the episodes. 2020 is notably a year with more dust episodes than other years in the 4-years time series we have studied here. The ternary plot for the top 10-population is shown in the right panel of Fig. 6.

Table 3: Top 10 mineral dust episodes.

Season	Start Date	End Date	Mineral Dust [μgm^{-3}]
MAM	13.05.2019	14.05.2019	2,2
MAM	15.05.2019	16.05.2019	2,0
DJF	06.01.2020	10.01.2020	2,4
MAM	13.04.2020	15.04.2020	2,9
SON	02.11.2020	04.11.2020	12,0
SON	09.11.2020	11.11.2020	5,9
SON	30.11.2020	02.12.2020	3,3
DJF	07.12.2020	09.12.2020	3,3
DJF	04.01.2021	06.01.2021	3,8
SON	15.11.2021	17.11.2021	3,2

4 Results

The dates with extreme dust events in the CAMS and FLEXDUST data sets are shown for the time period 2018-2021 in Fig. 7. See also Table 4 (Appendix A) for the CAMS dates. A total of 7 extreme dust events were identified in the CAMS reanalysis data. Far more events are identified in the FLEXDUST data. Part of the difference is due to the number of pixels included in the events as noted above. However, it is also known that the dust AOD in CAMS is low compared to other models (Xian et al., 2022a). Furthermore, other types of aerosols also contribute largely to the total aerosol optical depth in the identified extreme CAMS dust events.

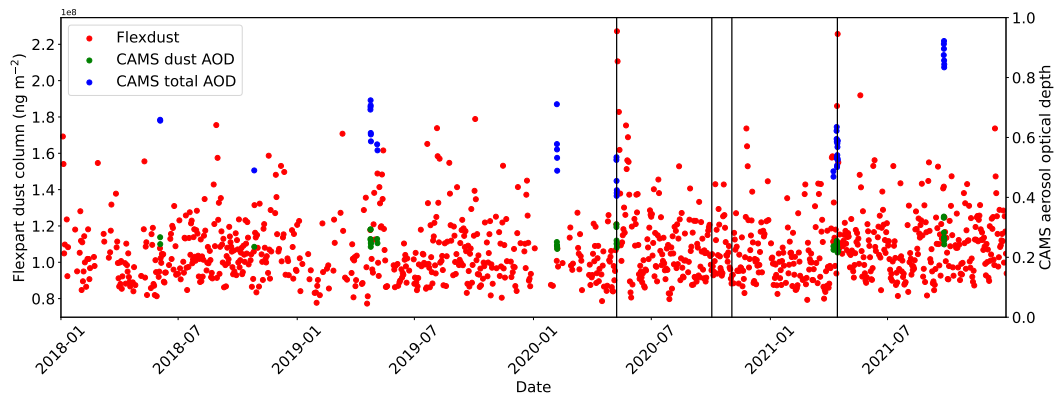


Figure 7: The FLEXDUST (red dots), CAMS total (blue dots) and dust (green dots) AOD for the times identified as extreme dust aerosol events using the FLEXDUST and CAMS reanalysis data for 2018-2021. Vertical black lines indicate dates for which detailed analysis was made.

There are few Arctic dust sources in the CAMS data, thus, no pure Arctic extreme dust aerosol event was identified in the CAMS data. The locations of the extreme dust events are shown in Fig. 8.

Not all dust events in the CAMS data stand out in the FLEXDUST data, compare green and red dots in Fig. 7. However, for 8 May 2020 and 14 April 2021 large dust values are present in both data sets. Furthermore, the aerosol episode over northern Europe in the beginning of October 2020 which was analysed by Groot Zwaafink et al. (2022) is of interest as the origin and type of aerosol present are well characterized for this episode. Finally, the large event seen in the Ny-Ålesund in-situ data on 2 November 2020 is included. Thus, for these four events, indicated by black lines in Fig. 7, further analysis including SLSTR data, were performed.

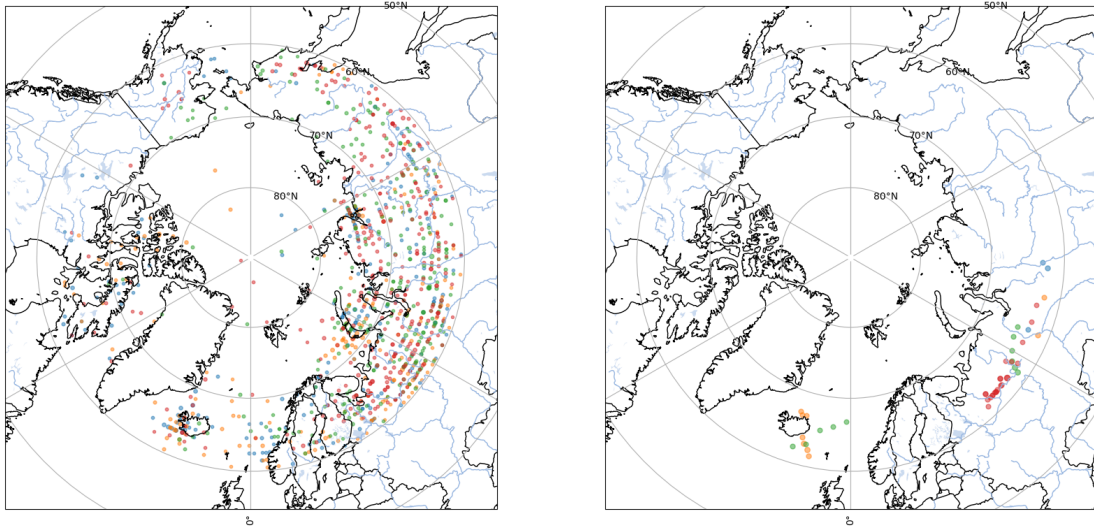


Figure 8: Location of extreme dust aerosol events in the FLEXDUST (left plot) and CAMS reanalysis (right plot) data for 2018-2021. Color codes different years: blue=2018; orange=2019; green=2020; red=2021.

4.1 Northern Europe October 2020 event

In Figs. 9 and 10 are CAMS aerosol optical depth and FLEXDUST column loading plots for the aerosol episode over northern Europe October 2020 which was analysed by Groot Zwaaftink et al. (2022). The October 2020 event was a mixed aerosol type event with a dust contribution between 23-45%. In the CAMS data used for identification of extreme dust events there is dust in the correct region for this event. However, the dust amount is not large enough to be identified as an extreme event, shown in Fig. 7 (as described in Section 3.1).

This event was visible in OLCI data over central Sweden and Norway, see Fig. 2 in Groot Zwaaftink et al. (2022), and as such provide a test ground to see if these aerosols may also be seen in the SLSTR dBT data. Radiative transfer simulations of the OLCI radiances indicated that the aerosol had an absorbing component and samples from three sites showed a mixed type of aerosol with mineral dust contributing by between 23-45% to PM_{10} (Groot Zwaaftink et al., 2022).

Both S3A and S3B were flying at the time of this event. Unfortunately, there are no data in the infrared S7, S8, and S9 channels of S3A for this event. However, S3B provided data. Unfortunately, the aerosol cloud was captured by the swath edges of S3B as seen in the RGB made from OLCI data, Fig. 11. In the left plot a darkening is seen between about 61°N and 62°N and 15°E and 20°E. A similar darkening is seen in the right plot west of 10°E. These darkenings over the bright underlying cloud and the Bothnian sea are in agreement with those seen in Fig. 2 of Groot Zwaaftink et al. (2022) and identified as aerosols.

Fig. 12 shows the brightness temperature difference between SLSTR channels S8 and S9 for nadir and oblique viewing directions and the same overpasses as in Fig. 11. It is noted that OLCI and SLSTR have different swath widths and thus the views in Figs. 11 and 12 are different. Furthermore, the SLSTR oblique view is narrower than the nadir view by design.

For the first overpass around 08:53, top row plots in Fig. 12, the aerosol seen in nadir view has negative dBT . This part of the aerosol cloud is not covered by the oblique view. The negative brightness temperature signature is observed over a bright underlying cloud, cf. left plot of Fig. 11. There is no negative dBT signature over water surfaces although aerosol are present there as seen in the RGB of Fig. 11. For the oblique view some negative values of the brightness temperature difference is observed over the western parts of the Murmansk oblast (upper right plot Fig. 12). For the second overpass around 10:34 there are no negative brightness temperature difference values in nadir view (lower left plot Fig. 12). There is a clear negative signal in the oblique view (lower right plot Fig. 12).

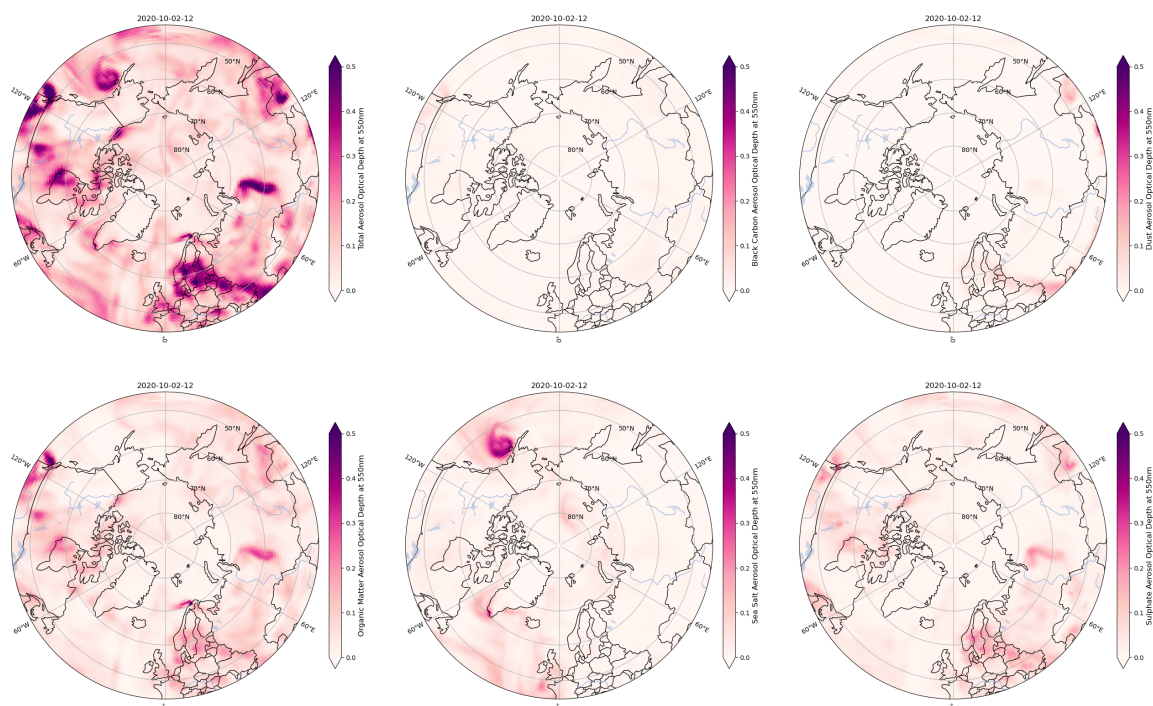


Figure 9: Aerosol optical depth from CAMS reanalysis for 2 October 2020, 12:00. The total, black carbon, dust, organic matter, sea salt and sulphate aerosol depth is shown from top left to bottom right.

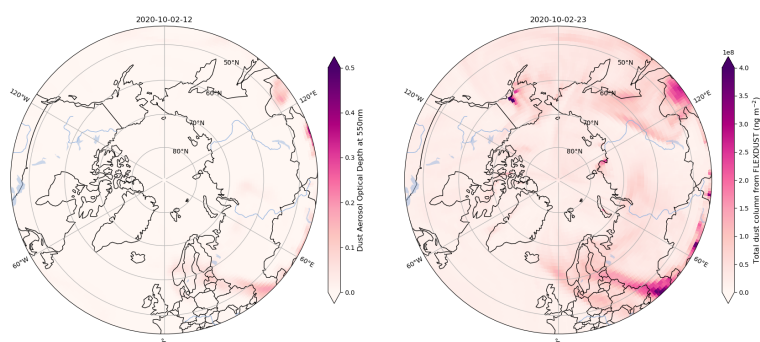


Figure 10: (left) Dust aerosol optical depth from CAMS reanalysis for 2 October 2020, 12:00. (right) Dust column amount from FLEXDUST for 2 October 2020.

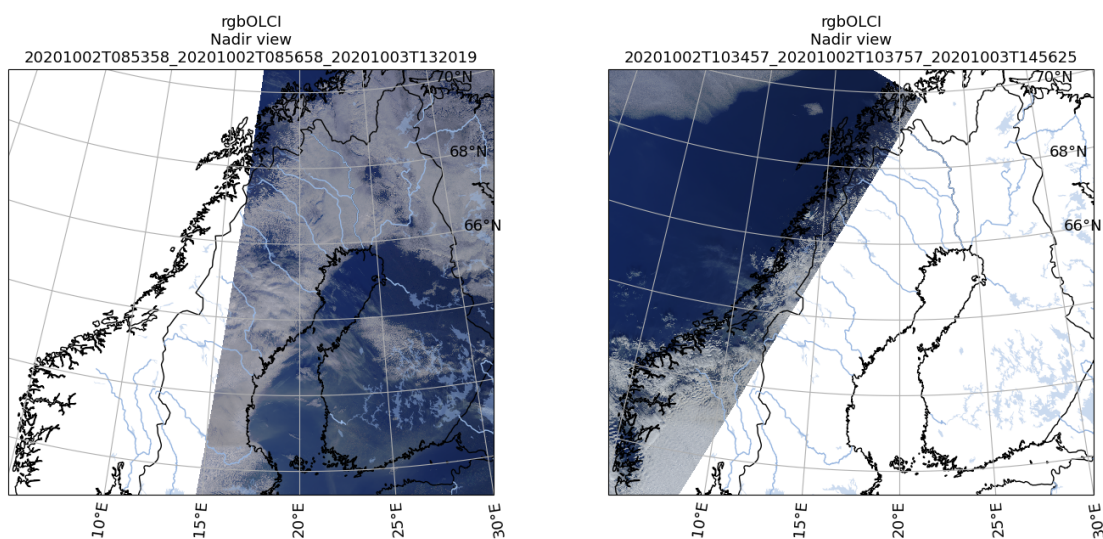


Figure 11: RGBs made from OLCI bands 3, 6, and 8 centred at 442.5, 560, and 665 nm. Data from 2 October 2020 at 08:53 (left) and 10:34 (right) UTC.

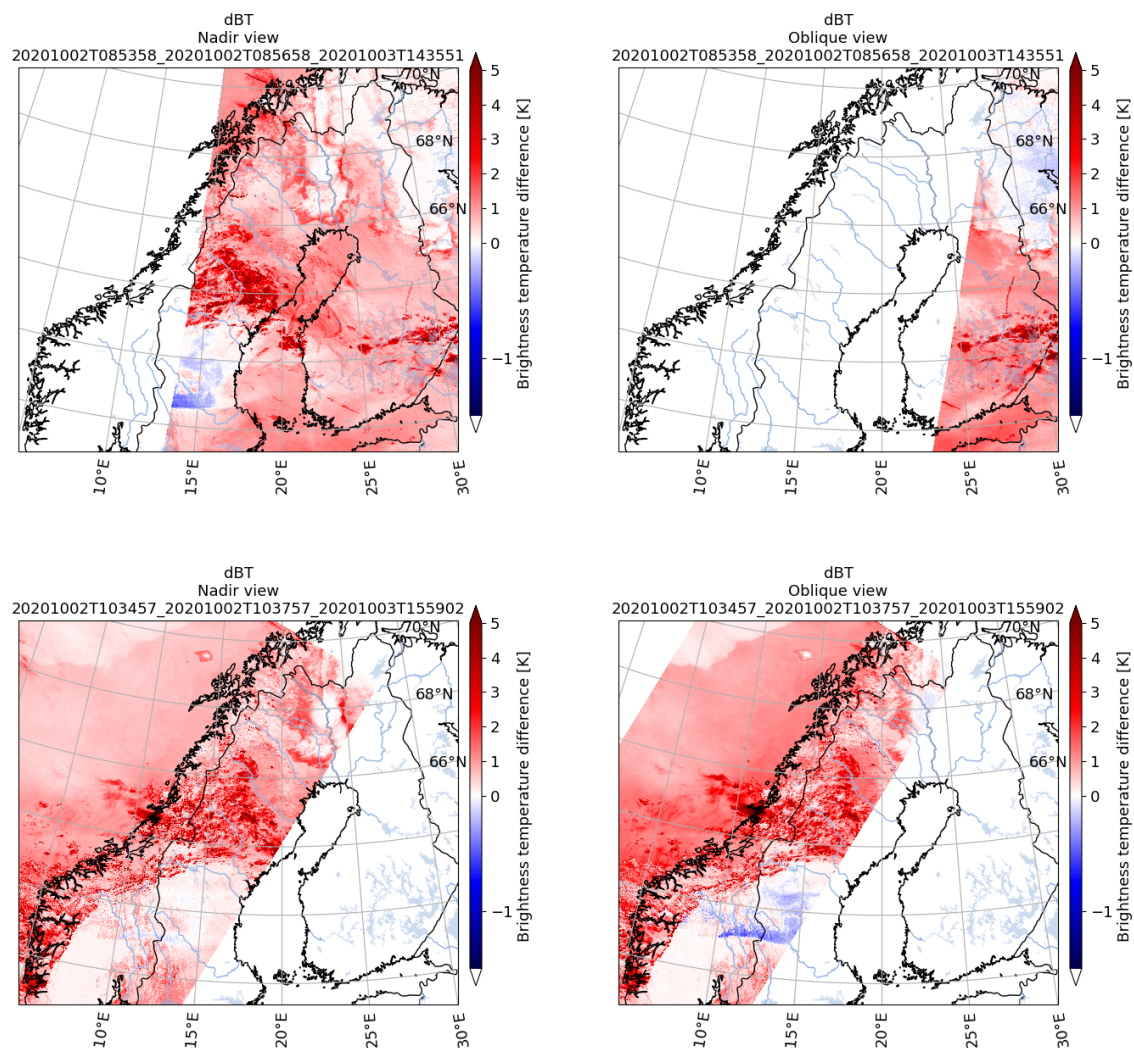


Figure 12: Brightness temperature difference between SLSTR channels S8 and S9 for nadir (left panels) and oblique (right panels) viewing directions for two overpasses on 2 October 2020, at around 08:53 (top panels) and 10:34 (bottom panels).

4.2 Dust over Russia

CAMS aerosol optical depth plots of two extreme dust events on 8 May 2020 and 14 April 2021 are shown in Figs. 1 and 13 respectively, for the different CAMSRA aerosol types. The corresponding dust concentrations from FLEXDUST are shown in Figs. 3 and 14. Both of these events are characterized by aerosol transported from lower latitudes and a relatively large contribution of dust to the total aerosol load as suggested by the CAMS aerosol typing.

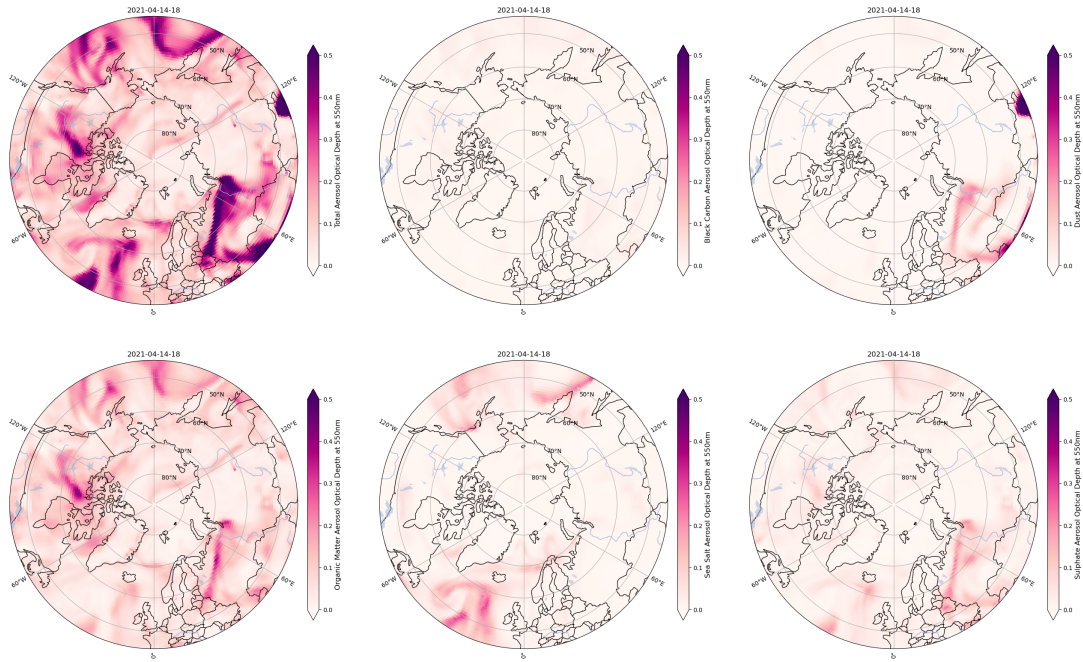


Figure 13: Aerosol optical depth from CAMS reanalysis for 14 April 2021, 18:00. The total, black carbon, dust, organic matter, sea salt and sulphate aerosol depth is shown from top left to bottom right.

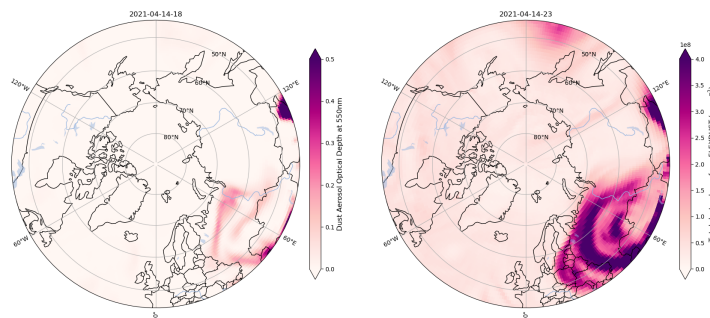


Figure 14: (left) Dust aerosol optical depth from CAMS reanalysis for 14 April 2021, 18:00. (right) Dust column amount from FLEXDUST for 14 April 2021.

4.2.1 SLSTR data 8 May 2020

In Fig. 15 is shown the brightness temperature differences $dB T$ from the SLSTR instrument from the daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 8 May 2020. The corresponding SLSTR S8 channel brightness temperatures are shown in Fig. 16.

In the daytime overpasses (about 10:00-13:00 local time) no negative $dB T$ is observed (upper row Fig. 15). In the nighttime overpasses negative $dB T$ are seen for all overpasses except the west most swath (lower row Fig. 15). Daytime aerosol for this event are seen by other satellites, for example in Visible Infrared Imaging Radiometer Suite (VIIRS) data³. Thus, this event is not detected in the daytime SLSTR $dB T$, but in the nighttime SLSTR $dB T$.

Compared to the CAMS and FLEXDUST data, Figs. 1 and 3, respectively, the satellite data indicates dust around the Kazakhstan-Russian border while CAMS and FLEXDUST places the aerosol further south. The aerosol feature starting in western Kazakhstan and protruding nearly all the way to the Kara sea is not seen in SLSTR data. This is most likely due to the aerosol being obscured by clouds (see for example RGB VIIRS data in footnote 3).

³[https://worldview.earthdata.nasa.gov/?v=-9.942191905952107,19.808959100674628,115.3477238729576,96.31652671916851&l=Reference_Labels_15m\(hidden\),Reference_Features_15m\(hidden\),Coastlines_15m,VIIRS_SNPP_AOT_Deep_Blue_Best_Estimate,VIIRS_NOAA20_CorrectedReflectance_TrueColor\(hidden\),VIIRS_SNPP_CorrectedReflectance_TrueColor,MODIS_Aqua_CorrectedReflectance_TrueColor\(hidden\),MODIS_Terra_CorrectedReflectance_TrueColor\(hidden\)&lg=true&t=2020-05-08-T09%3A21%3A23Z](https://worldview.earthdata.nasa.gov/?v=-9.942191905952107,19.808959100674628,115.3477238729576,96.31652671916851&l=Reference_Labels_15m(hidden),Reference_Features_15m(hidden),Coastlines_15m,VIIRS_SNPP_AOT_Deep_Blue_Best_Estimate,VIIRS_NOAA20_CorrectedReflectance_TrueColor(hidden),VIIRS_SNPP_CorrectedReflectance_TrueColor,MODIS_Aqua_CorrectedReflectance_TrueColor(hidden),MODIS_Terra_CorrectedReflectance_TrueColor(hidden)&lg=true&t=2020-05-08-T09%3A21%3A23Z)

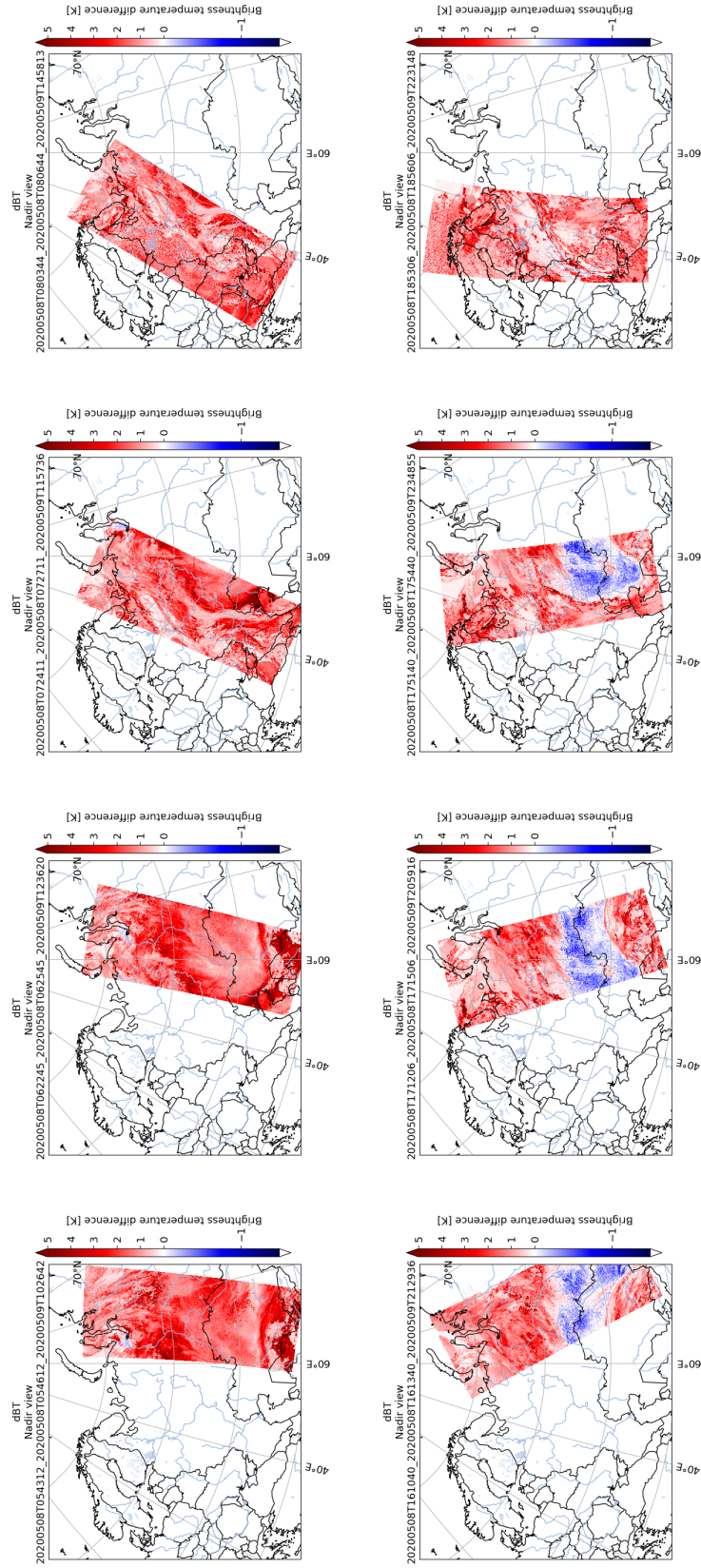


Figure 15: Brightness temperature differences from the SLSTR instrument from daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 8 May 2020.

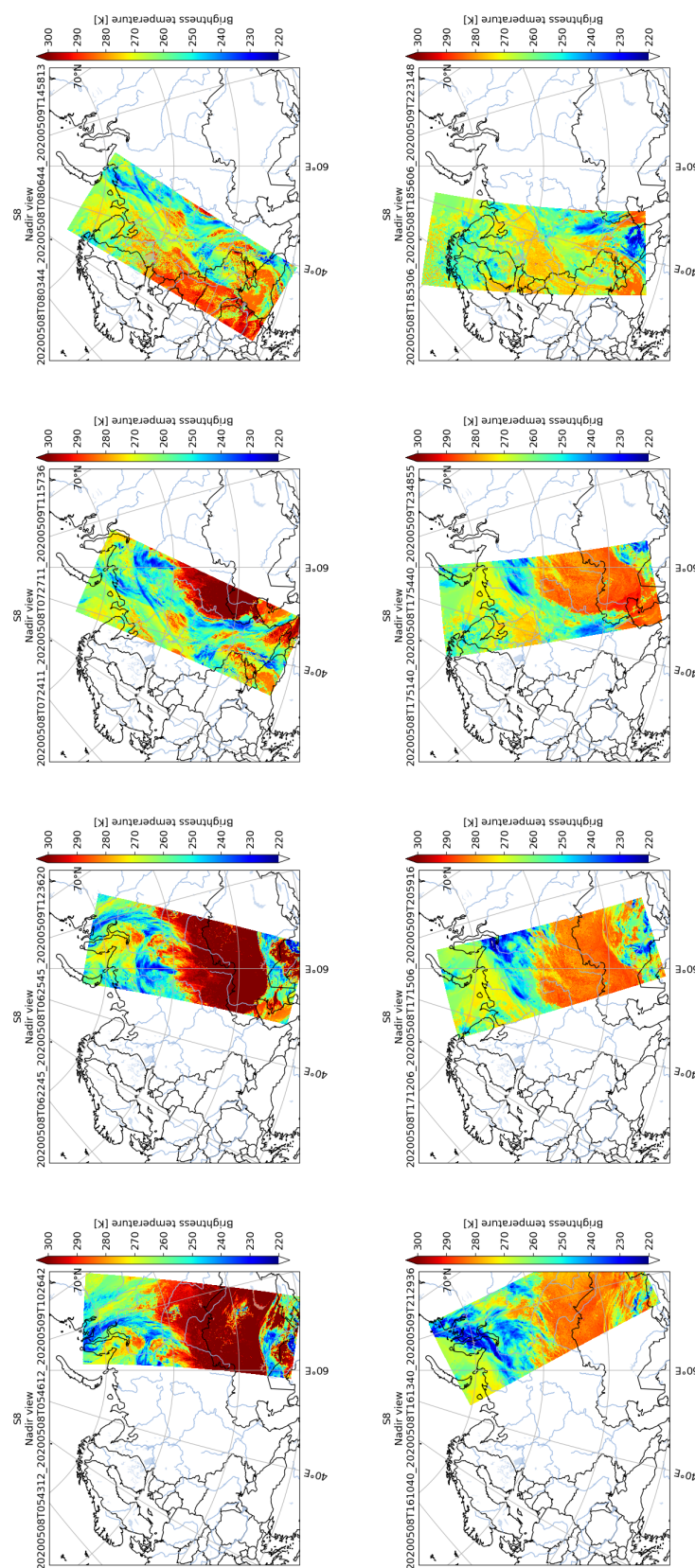


Figure 16: Brightness temperature from the S8 SLSTR channel for daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 8 May 2020.

4.2.2 SLSTR data 14 April 2021

In Fig. 17 the brightness temperature differences from the SLSTR instruments from the daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 14 April 2021 is shown. The corresponding SLSTR S8 channel brightness temperatures are shown in Fig. 18.

Similar as the 8 May 2020 event, for the daytime overpasses no negative $dB T$ s are present. For the nighttime overpasses an extensive region has negative $dB T$ s. This region agrees with the one seen by for example VIIRS and identified as aerosol⁴. The CAMS and FLEXDUST data, Figs. 13 and 14, show the presence of aerosol throughout the whole day in contrast to the SLSTR data which does not show any aerosol in the daytime overpasses. The extent of the aerosol is rather different in the CAMS, FLEXDUST and the SLSTR data. CAMS and FLEXDUST, Fig. 14, locate most of the aerosol around the western Kazakhstan-Russia border and protruding towards the Kara sea, while SLSTR have negative $dB T$ s over more or less the whole of Kazakhstan with no aerosol towards the Kara sea. The latter may be due to the presence of clouds (see VIIRS RGB in footnote 4).

The lack of negative $dB T$ during daytime for both the 8 May 2020 and 14 April 2021 events may be due to larger brightness temperature values observed over the dust affected regions during daytime (compare upper and lower rows of Figs. 16 and 18). Also recall the discussion in section 2.2 and the possibility for a temperature inversion. For the 14 April 2021 event the FLEXDUST dust profiles for PM_{10} , $PM_{2.5}$, PM_{10} and PM_{20} are shown in Fig 19 together with the ERA5 temperature profiles for daytime and nighttime. The data covers a longitude band between 50-60°E at the latitude 53°N. This covers the dust cloud seen in Fig. 17.

The dust detection sensitivity varies with particle size. For volcanic ash Stohl et al. (2011) reported a sensitivity peaking for particles with a diameter of about 8 μm , see their Fig. 1. Dust and volcanic ash in general have different optical properties. However, dust retrievals are most likely also sensitive to smaller sizes. Hence, the $PM_{2.5}$ and PM_{10} profiles may be most representative for what the satellite sense. Both these size ranges have an extensive peak between about 2000-4000 m and elevated surface amounts. Note that the dust profiles are daily averages and do not show any diurnal variations.

For the temperature there is a clear inversion at altitudes between 500-1000 m for daytime profiles (light blue in Fig. 19, while for the nighttime profiles (green) the inversion is close to the ground. The elevated temperature inversion for the daytime may support the simplified explanation section 2.2 for the lack of detection of dust during daytime. However, detailed radiative transfer simulations are required to fully understand the detection capabilities of dust using the SLSTR S8 and S9 channels. This is beyond the scope of the present study.

Finally, note that VIIRS also detects some aerosol over the seas north of the Kola peninsula of optical depth up to 0.1 at 550 nm. There is no negative $dB T$ for this region in the SLSTR data.

In the Appendix B daytime AOD from TROPOMI onboard Sentinel 5P (PAL data product) and the SLSTR/OCLI onboard of Sentinel3 SYNERGY AOD for 14 April 2021 are shown. In addition images visualizing CALIOP/CALIPSO data for day and night-time during the 14 April 2021 are given. The CALIOP aerosol classifications indicates dust, both during day and night-time (as expected this is less clear during daytime, due to reduced signal-to-noise ratio). TROPOMI AOD at 494 nm seems somewhat enhanced, the SLSTR/OCLI AOD at 550 nm is relatively low, and further analysis is required to interpret the data with respect to the SLSTR detection capability. The closest AEROSOL ROBOTIC NETWORK (AERONET)(e.g. Holben et al., 1998) sites are Yekaterinburg (Russia, 57.03833°N, 59.54500°E, 300 m a.m.s.l), and Tomsk (Russia, 56.47535°N, 85.04806°E, 174 m a.m.s.l). On 14 April 2021 no data were obtained.

⁴[https://worldview.earthdata.nasa.gov/?v=-9.942191905952107,19.808959100674628,115.3477238729576,96.31652671916851&l=Reference_Labels_15m\(hidden\),Reference_Features_15m\(hidden\),Coastlines_15m,VIIRS_SNPP_AOT_Deep_Blue_Best_Estimate,VIIRS_NOAA20_CorrectedReflectance_TrueColor\(hidden\),VIIRS_SNPP_CorrectedReflectance_TrueColor,MODIS_Aqua_CorrectedReflectance_TrueColor\(hidden\),MODIS_Terra_CorrectedReflectance_TrueColor\(hidden\)&lg=true&t=2021-04-14-T09%3A21%3A23Z](https://worldview.earthdata.nasa.gov/?v=-9.942191905952107,19.808959100674628,115.3477238729576,96.31652671916851&l=Reference_Labels_15m(hidden),Reference_Features_15m(hidden),Coastlines_15m,VIIRS_SNPP_AOT_Deep_Blue_Best_Estimate,VIIRS_NOAA20_CorrectedReflectance_TrueColor(hidden),VIIRS_SNPP_CorrectedReflectance_TrueColor,MODIS_Aqua_CorrectedReflectance_TrueColor(hidden),MODIS_Terra_CorrectedReflectance_TrueColor(hidden)&lg=true&t=2021-04-14-T09%3A21%3A23Z)

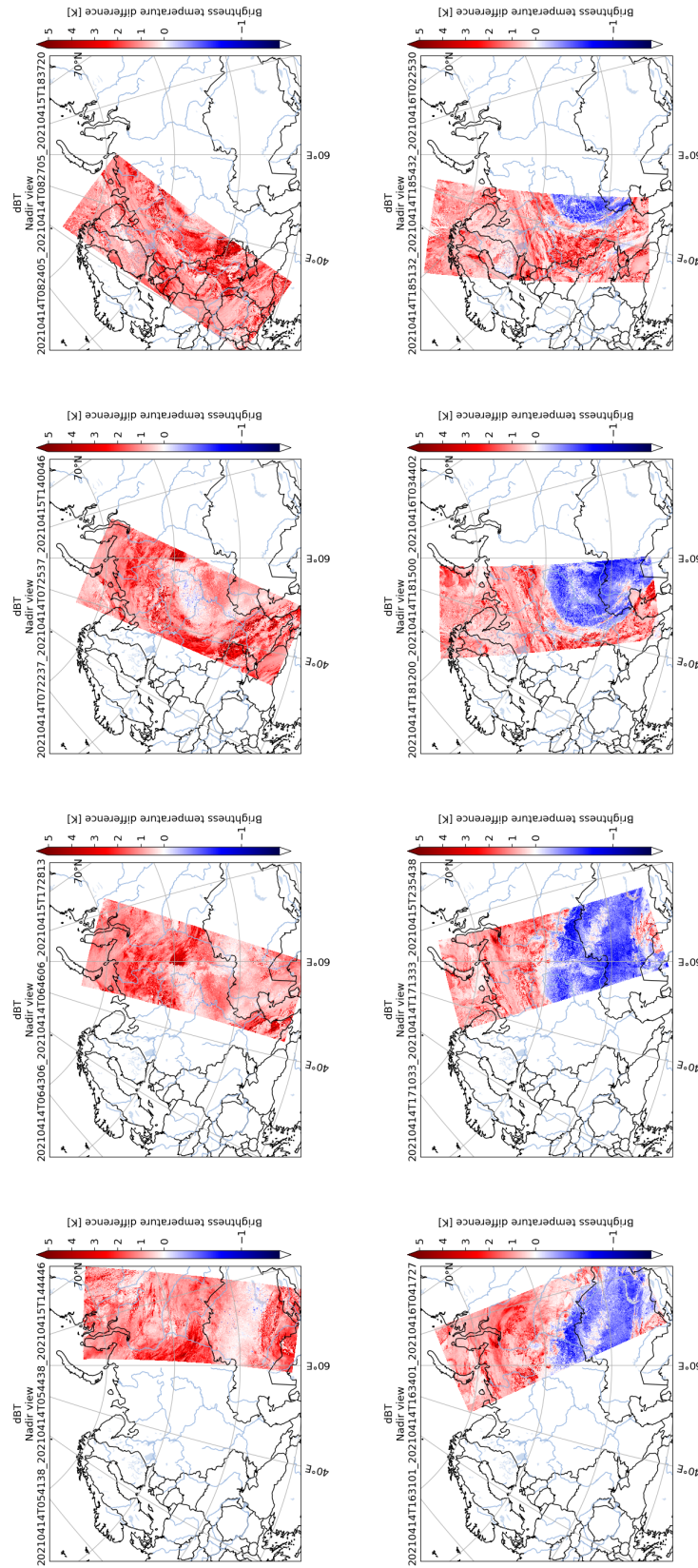


Figure 17: Brightness temperature differences from the SLSTR instrument from daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 14 April 2021.

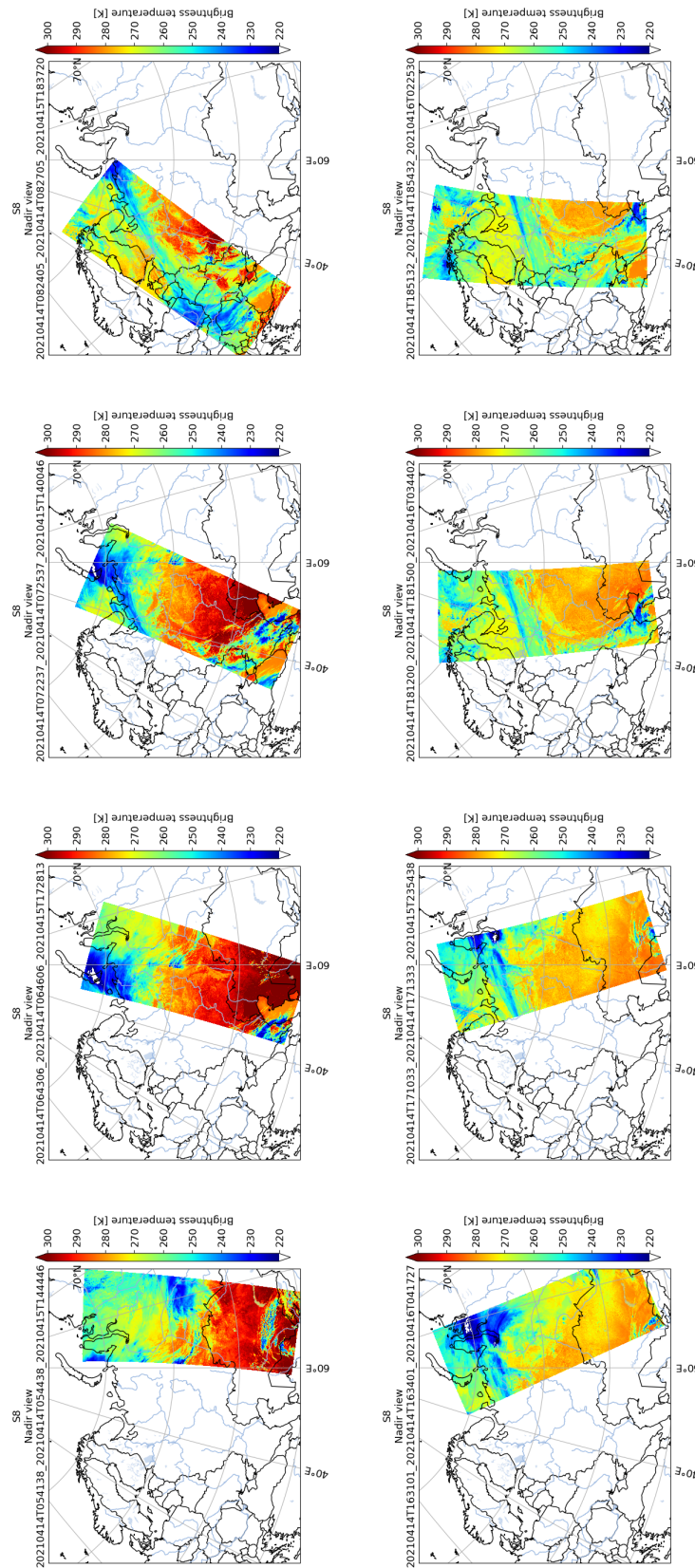


Figure 18: Brightness temperature from the S8 SLSTR channel for daytime (upper row) and nighttime (lower row) overpasses of the S3A and S3B satellites on 14 April 2021.

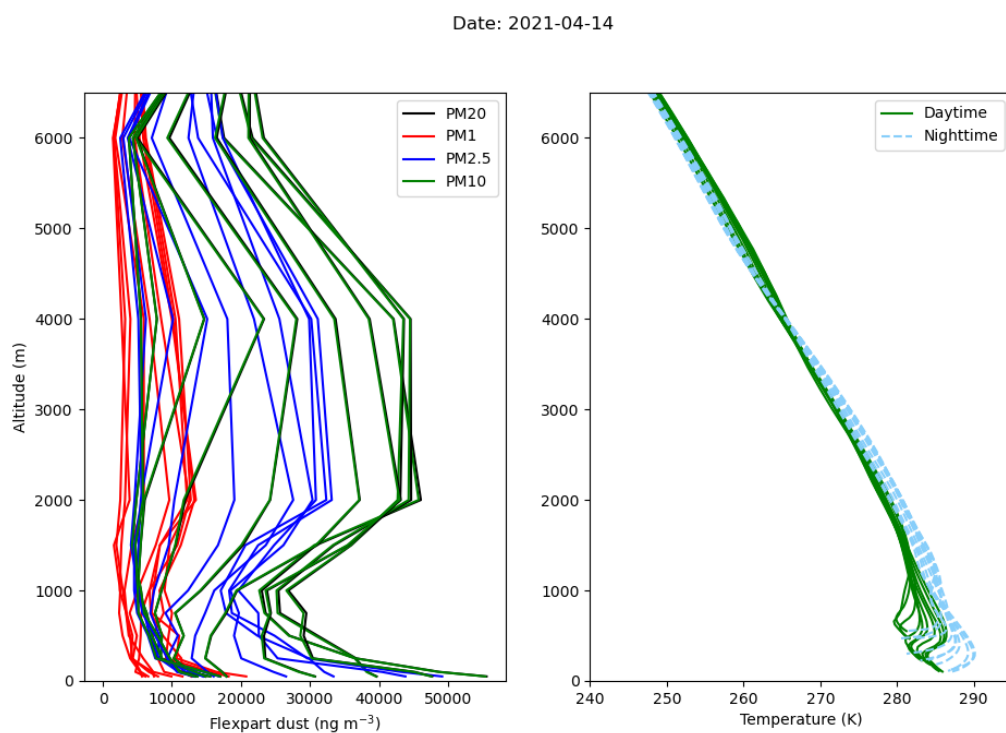


Figure 19: (Left) FLEXDUST dust profiles for PM₁, PM_{2.5}, PM₁₀ and PM₂₀. (Right) ERA5 temperature profiles for daytime and nighttime. Data are for 14 April 2021 and longitudes between 50-60°E and latitude 53°N.

4.3 Surface dust episodes in Ny-Ålesund

4.3.1 Top 10 strongest in-situ episodes

The major dust episodes registered via filter sample measurements taken in Ny-Ålesund are listed in Table 3.

The inter correlations for the surface measurements (Table 2) show that Al, Fe, Ti, and Mn (Mineral Dust) correlates highly, as do As and Pb (anthropogenic). No correlation is found between mineral dust and anthropogenic species. The resulting ternary plot is shown in Fig. 6. $\text{Al} - \text{Fe} \times 2 - \text{Ti} \times 30$ is used to illustrate the spread in relative composition of mineral dust elements. The ternary plots of the full series and the top-10 dust events do not show large variability, nor a spread towards one specific corner, which indicates a lack of diversity and no dominance of a particular component. This could suggest a common source or similar types of sources for the dust throughout the time series. If the dust is being transported over long distances, a lack of variability in the mineral composition could suggest that the transport process does not significantly alter the composition of the dust.

There is one significant episode in October 2020, clearly visible from the time series. This mineral dust episode is, however, not wholly covered by this dataset. Groot Zwaftink et al. (2022) covers this episode by a filter running from 02.10. - 10.10.2020, where a low ($5.6 - 7.6 \mu\text{g m}^{-3}$) and a high ($7.2 - 8.6 \mu\text{g m}^{-3}$) estimate of the mineral dust concentration was provided. The low estimate corresponds to the formula used in the present data compilation.

The CAMS total aerosol optical depth is shown in Fig. 20 for 2 Nov 2020 for 18:00 (left plot) and 21:00 (right plot). Note the presence of aerosol between Iceland and Spitsbergen. Also, note the aerosol extending from east of Spitsbergen and towards the south east. CAMS types these aerosol as sea salt aerosol.

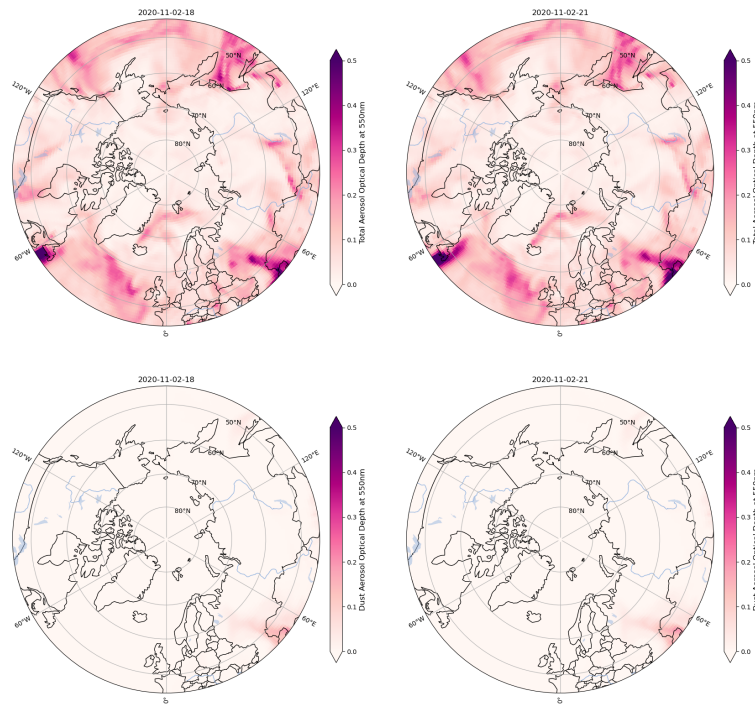


Figure 20: Total (upper row) and dust (lower row) aerosol optical depth from CAMS reanalysis for 2 November 2020, 18:00 (left) and 21:00 (right).

4.3.2 IASI data 13 May 2019

For studies of the episode mid-May 2019 we have used dust aerosol data from the LMD algorithm which analyse METOP-A IASI data⁵. Dust AOD is shown in Fig. 21. Data from 12 May to 17 May 2019 are plotted, starting from the left corner and read rightwards. Two filters were collected at the Zeppelin observatory during the same time period, marked with red (13-14 Feb) and blue (15-16 Feb) frames in the plot.

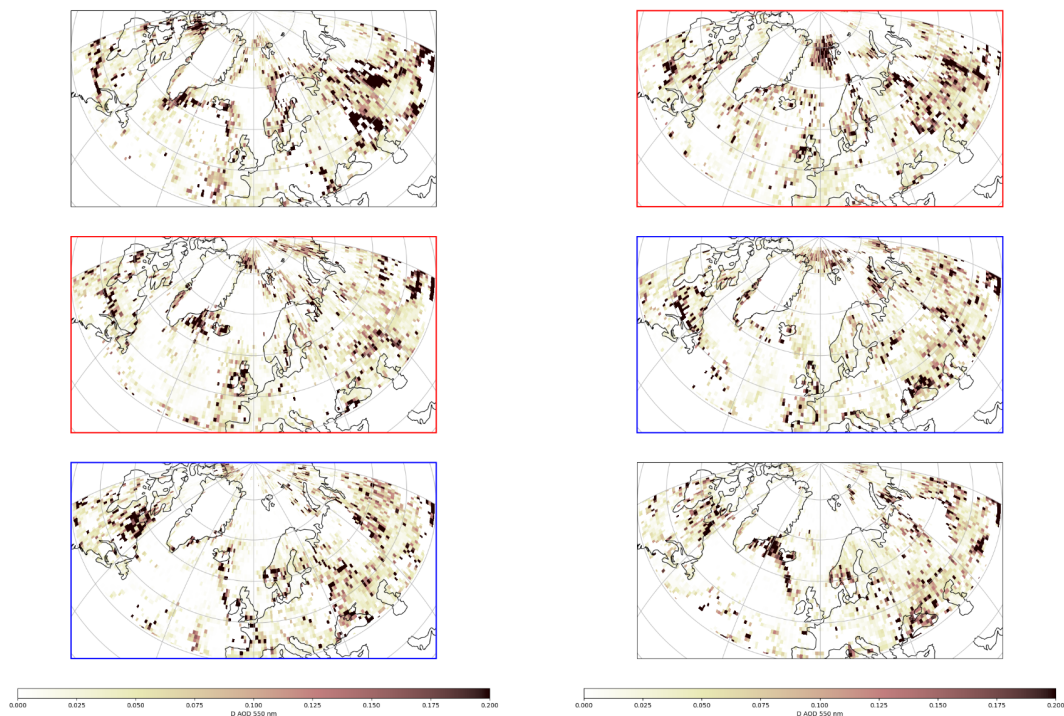


Figure 21: IASI METOP-A LMD dust-AOD (at 550 nm) 12-17 May 2019.

4.3.3 IASI data 2 November 2020

For studies of the clear episode in beginning of November 2020 we have used data from IASI data onboard METOP-C. Dust AOD at 550 nm is shown in Fig. 22. Data from the first 3 days of November are plotted, starting from 1 November in the left corner and read rightwards.

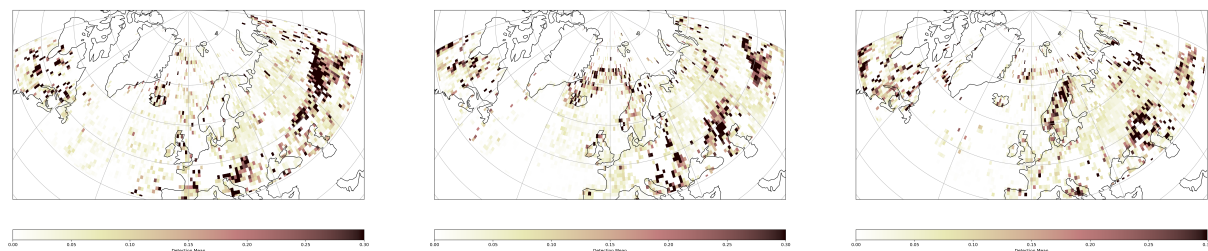


Figure 22: IASI METOP-C LMD dust-AOD (at 550 nm)m 1-3 November 2020.

⁵C3S PUGs: https://wdc.dlr.de/C3S_312b_Lot2/Documentation/AER/C3S2_312a_Lot2_PUGS_AER_latest.pdf

4.3.4 SLSTR data 2 November 2020

The SLSTR brightness temperature difference is shown for several overpasses for the region between Iceland and Spitsbergen in Fig. 23 for 2 November 2020. The CAMS reanalysis data suggests that aerosol should be present in this region, see Fig. 20. However, no negative $dB T$ values are present between Iceland and Spitsbergen nor over Spitsbergen. This may be due to cloud cover as indicated by the low S8 temperatures over parts of the northern Atlantic, Fig. 24. Though, the south east coast of Greenland appears cloud free and in principle aerosol should be detectable there.

The CAMS data also indicate aerosol on the east of Spitsbergen and protruding towards the south east, Fig. 20. Careful inspection of the top row, second and third column plots in Fig. 23, reveals some pixels with negative $dB T$ in this region in agreement with the CAMS data. There are also negative $dB T$ s over north-west Russia, which coincides with the aerosol in CAMS. Finally, some negative $dB T$ values are observed over central Greenland and the Queen Elisabeth islands. CAMS reports no aerosol for these regions.

5 Discussion

Detection of aerosol using infrared radiation observed by satellites may allow global year round night and day observations in contrast to visible radiation methods which require the presence of sun light. However, infrared detection depends on aerosol type, cloud presence, surface emissivity and ambient temperature conditions which all may inhibit aerosol detection. Here, cases where dust type aerosol were expected to be found in the Arctic based on in-situ surface data and CAMS and FLEXDUST model data, have been inspected to see if the infrared channels of SLSTR could detect these aerosol. The following findings were made:

- The SLSTR $dB T$ method allows dust aerosol detection over land surfaces under certain conditions. See sections 4.2.1 and 4.2.2.
- In agreement with OLCI findings, SLSTR $dB T$ method detects aerosol over clouds, see section 4.1.
- While OLCI detects aerosol, SLSTR $dB T$ method gives no detection over ocean, see section 4.1. However, for the south-east Spitsbergen case a $dB T$ signal is present over the ocean, section 4.3.4. Due to lack of sunlight, no visible radiation observations are available for this case to confirm the presence of aerosol.
- CAMS suggest the presence of aerosol between Iceland and Spitsbergen on 2 November 2020. No SLSTR $dB T$ signal is present in this region, see section 4.3.4. CAMS types these aerosol as sea salt. Infrared aerosol detection of aerosol is mostly sensitive to coarse mode aerosol, and in addition to dust and volcanic ash, sea salt is the only other aerosol with a coarse mode (Pierangelo et al., 2004).

In addition it is noted that local sources typically have larger concentrations close to the ground while long-range transported dust is seen at higher altitudes. Thus, satellite observations of dust from local sources may be hindered due to the presence of clouds, while long-range transported dust may be observed above clouds, see for example Fig. 2 in Groot Zwaftink et al. (2022). Also, Xian et al. (2022b) compared different aerosol climatologies in the Arctic for 2003–2019. For coarse mode AOD, which was taken to be representative for dust, the CAMSRA results behaved the worst in terms of r^2 when compared to monthly binned surface and satellite AODs from various Arctic stations.

Of the top 10 highest detected episodes on the ground-based in-situ filter samples, 7 of these were in the NH fall (4) or winter (3) season. 3 episodes were found during spring, and there were no top-10 dust episodes in the summer for the 4 years long dataset.

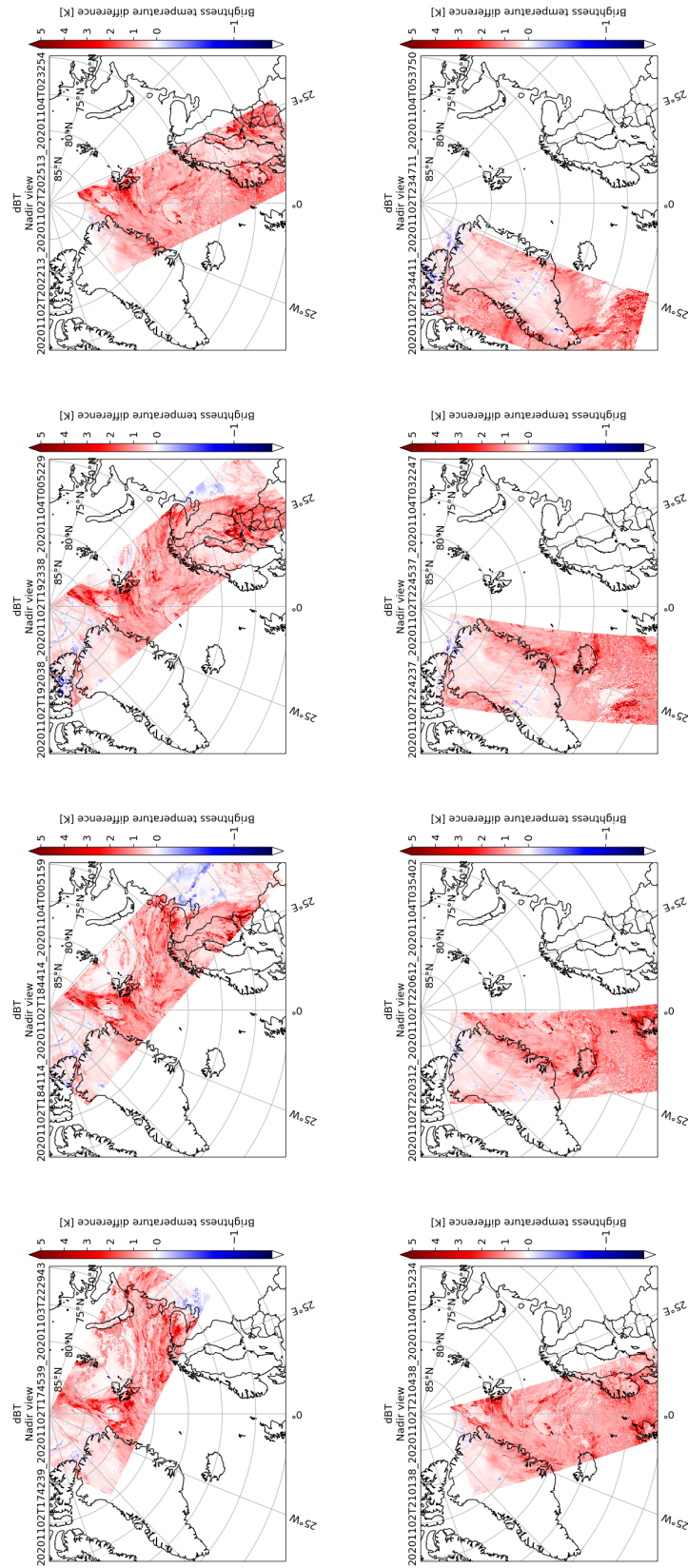


Figure 23: Brightness temperature differences from the SLSTR instrument overpasses of the S3A and S3B satellites on 2 November 2020.

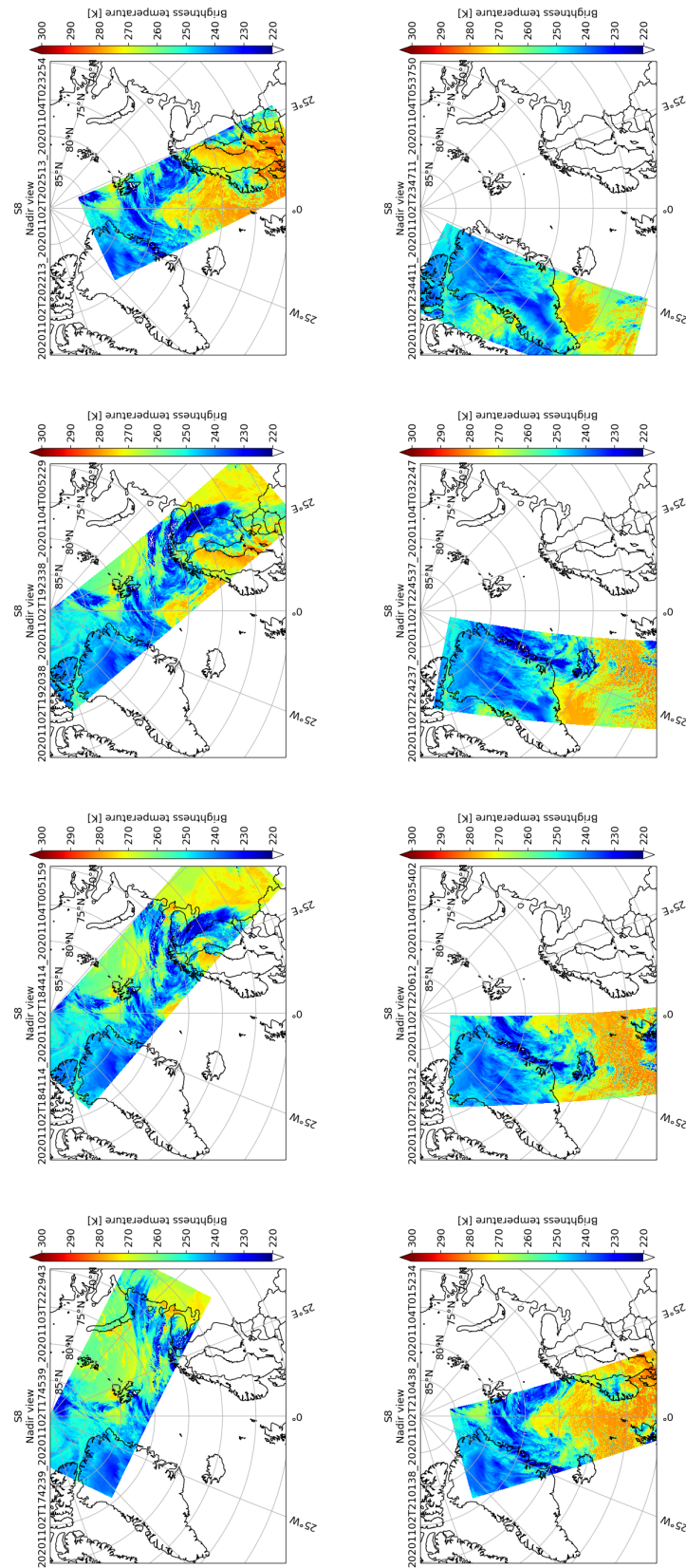


Figure 24: Brightness temperature from the S8 SLSTR channel for overpasses of the S3A and S3B satellites on 2 November 2020.

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A Extreme dust events in the CAMS data

Table 4 gives the date, size (in pixels) and location of the extreme dust events identified in the CAMSRA data set north of 60° for the time period 2018-2021.

Table 4: Extreme dust events in the CAMS data set.

Datetime (yyyy-mm-dd-hh)	No. pixels	Total AOD	Dust AOD	Min latitude	Max latitude	Min longitude	Max longitude
2018-06-03-06	17	0.659	0.267	61.50	63.75	85.50	88.50
2018-06-03-09	23	0.656	0.244	61.50	66.00	87.00	90.00
2018-10-26-15	22	0.490	0.235	61.50	63.75	65.25	71.25
2019-04-24-03	13	0.693	0.261	61.50	62.25	-14.25	-9.00
2019-04-24-06	20	0.702	0.293	61.50	63.00	-15.00	-10.50
2019-04-24-09	25	0.724	0.293	61.50	63.75	-16.50	-12.00
2019-04-24-12	23	0.707	0.257	63.00	66.00	-17.25	-12.75
2019-04-24-15	17	0.615	0.235	64.50	67.50	-17.25	-14.25
2019-04-24-18	17	0.610	0.248	66.00	68.25	-18.75	-15.75
2019-04-24-21	16	0.587	0.246	66.00	69.00	-19.50	-17.25
2019-05-04-12	13	0.577	0.261	61.50	62.25	64.50	70.50
2019-05-05-00	12	0.557	0.247	61.50	63.00	75.75	80.25
2020-02-06-03	16	0.711	0.251	61.50	63.00	-18.75	-15.00
2020-02-06-06	28	0.578	0.239	61.50	66.00	-15.75	-12.00
2020-02-06-09	36	0.560	0.240	62.25	67.50	-12.00	-8.25
2020-02-06-12	31	0.532	0.237	63.75	68.25	-7.50	-3.75
2020-02-06-15	17	0.489	0.228	64.50	68.25	-3.00	0.75
2020-05-08-03	14	0.525	0.301	61.50	62.25	51.75	57.75
2020-05-08-06	29	0.534	0.310	61.50	63.00	51.75	60.00
2020-05-08-09	34	0.455	0.256	61.50	63.75	53.25	63.00
2020-05-08-12	21	0.405	0.244	62.25	64.50	56.25	64.50
2020-05-08-15	16	0.415	0.247	63.75	65.25	60.75	67.50
2020-05-08-18	13	0.424	0.233	63.75	65.25	63.75	69.75
2021-04-08-09	16	0.487	0.237	61.50	63.00	55.50	60.00
2021-04-08-12	14	0.469	0.225	61.50	64.50	56.25	60.00
2021-04-13-06	26	0.622	0.241	61.50	63.00	36.75	46.50
2021-04-13-09	42	0.595	0.251	61.50	63.75	36.75	49.50
2021-04-13-12	42	0.635	0.255	61.50	63.75	37.50	51.75
2021-04-13-15	34	0.586	0.250	61.50	63.75	39.00	51.75
2021-04-13-18	29	0.530	0.246	61.50	63.00	39.00	52.50
2021-04-13-21	35	0.535	0.241	61.50	63.00	38.25	55.50
2021-04-14-00	36	0.501	0.236	61.50	63.00	37.50	56.25
2021-04-14-03	48	0.507	0.233	61.50	63.75	37.50	57.75
2021-04-14-06	53	0.532	0.233	61.50	63.75	37.50	61.50
2021-04-14-09	42	0.541	0.225	61.50	63.75	38.25	63.00
2021-04-14-12	39	0.580	0.225	61.50	64.50	40.50	65.25
2021-04-14-15	21	0.568	0.223	61.50	64.50	42.75	68.25
2021-04-14-18	11	0.529	0.216	62.25	64.50	58.50	70.50
2021-04-15-00	27	0.525	0.221	61.50	64.50	67.50	73.50
2021-04-15-03	25	0.589	0.220	61.50	64.50	71.25	78.75
2021-09-25-21	23	0.875	0.332	61.50	63.75	50.25	55.50
2021-09-26-00	27	0.912	0.336	61.50	64.50	49.50	54.00
2021-09-26-03	35	0.896	0.283	61.50	66.00	48.75	54.00
2021-09-26-06	22	0.922	0.266	61.50	65.25	48.00	52.50
2021-09-26-09	20	0.857	0.264	61.50	64.50	47.25	51.75
2021-09-26-12	20	0.834	0.256	61.50	64.50	46.50	51.00
2021-09-26-15	15	0.844	0.243	61.50	63.75	45.75	48.75

**B TROPOMI/S-5P PAL AOD, SLSTR/OCLI/S-3 SYNERGY AOD and
CALIOP/CALIPSO data for 14 April 2021**

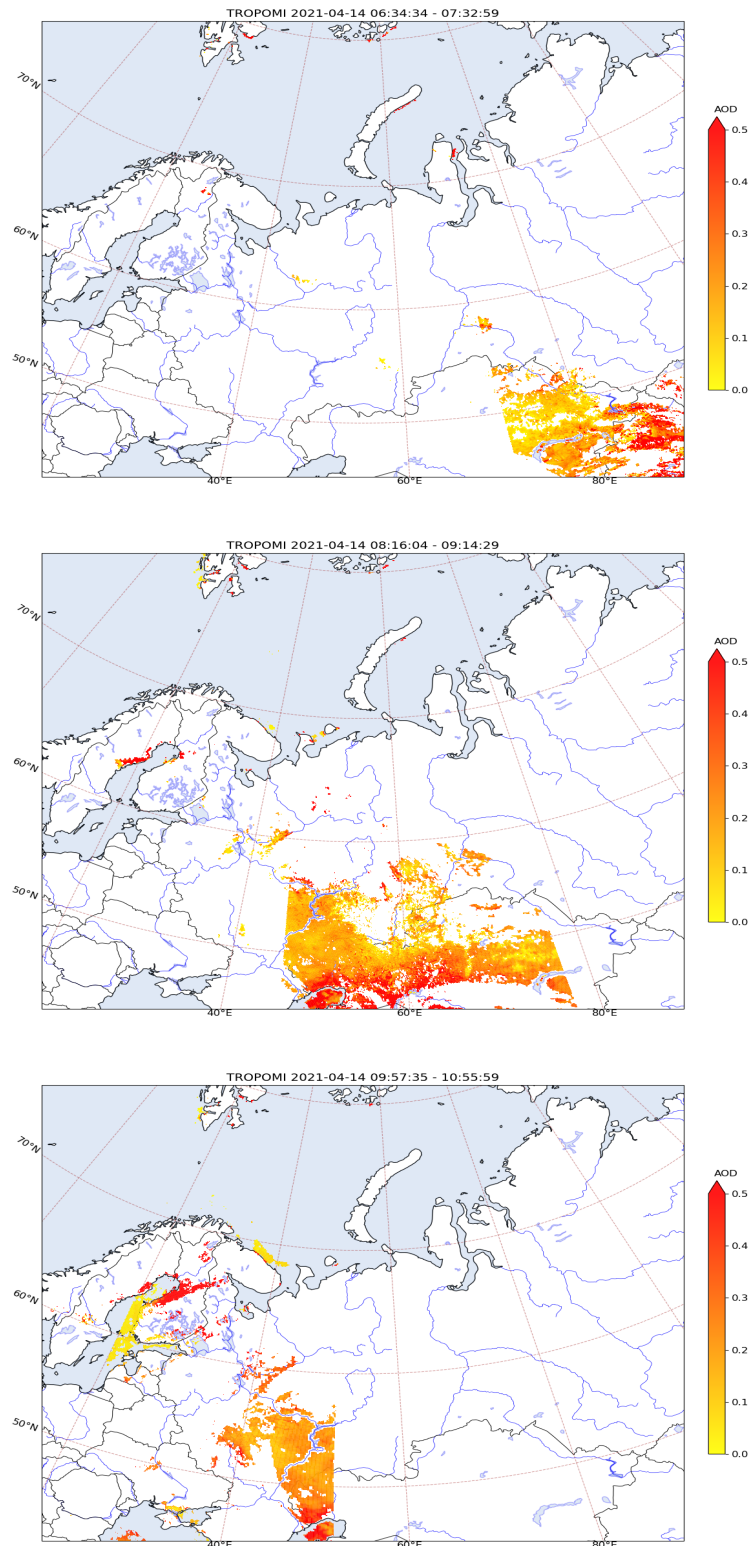


Figure 25: Aerosol optical depth at 494 nm from TROPOMI (PAL data product, with recommended quality flag $qa > 0.5$) for 14 April 2021.

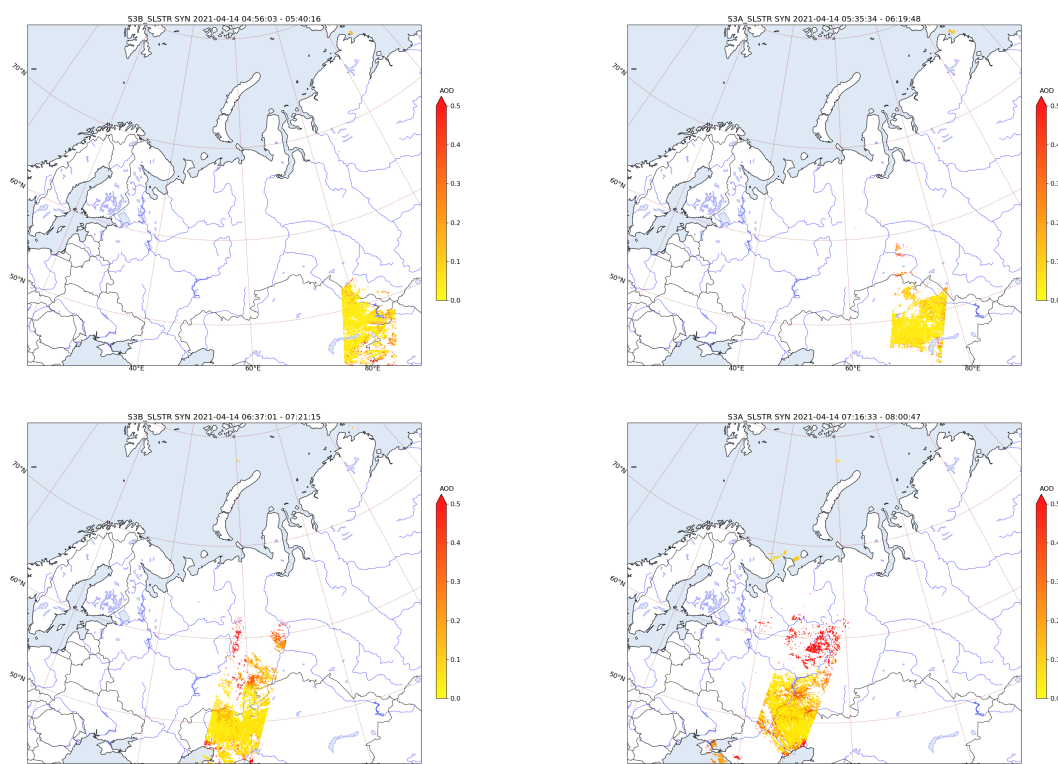


Figure 26: Aerosol optical depth at 550 nm from SLSTR/OCLI (Sentinel 3B (left panel), Sentinel 3A (right panel) Synergy data product) for the 14 April 2021.

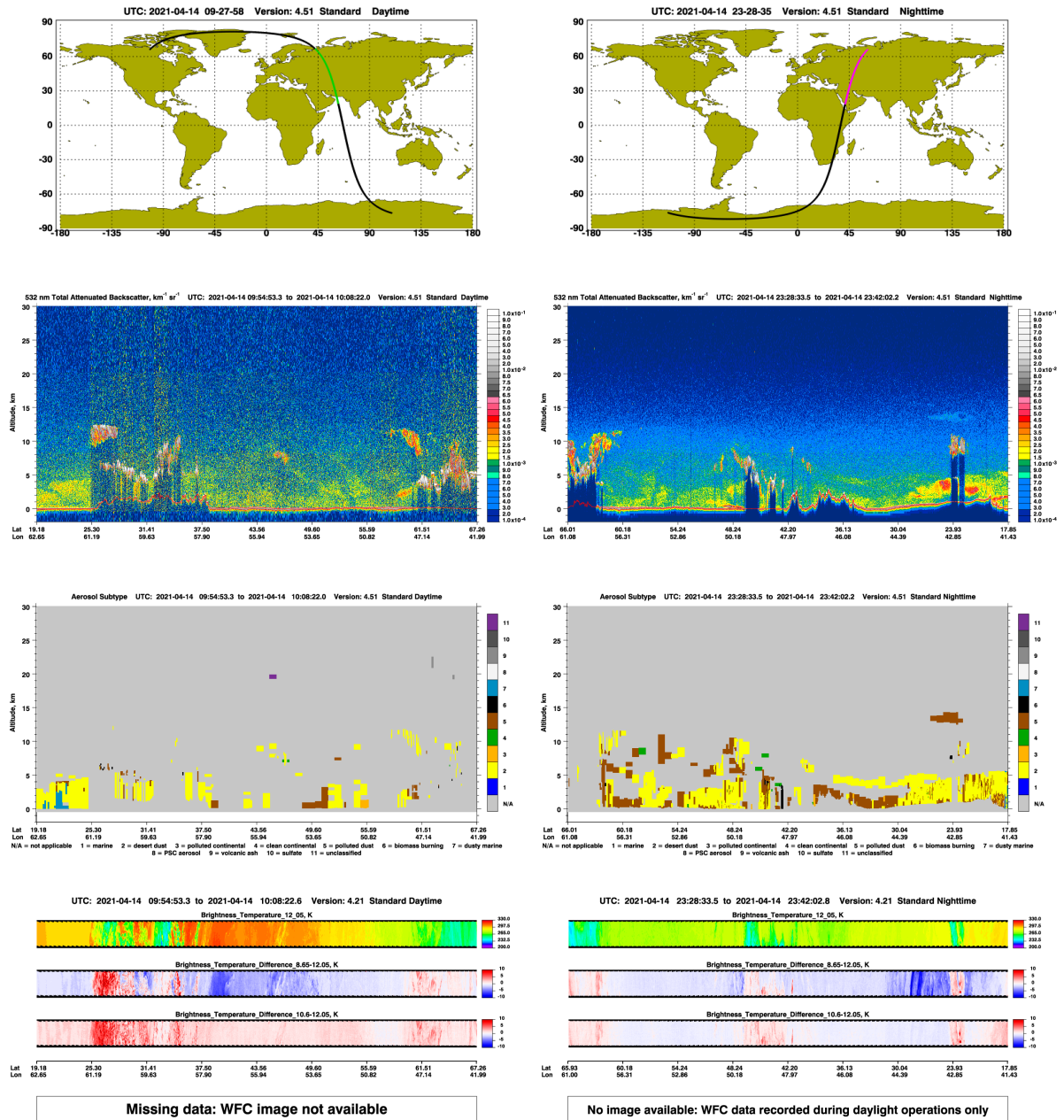


Figure 27: CALIOP daytime (left panel) and night-time (right panel) data for 14 April 2021.

C SLSTR AOD product 2018-2021

On the dataspace.copernicus.eu five overpasses for SLSTR AOD at 550 nm are available.

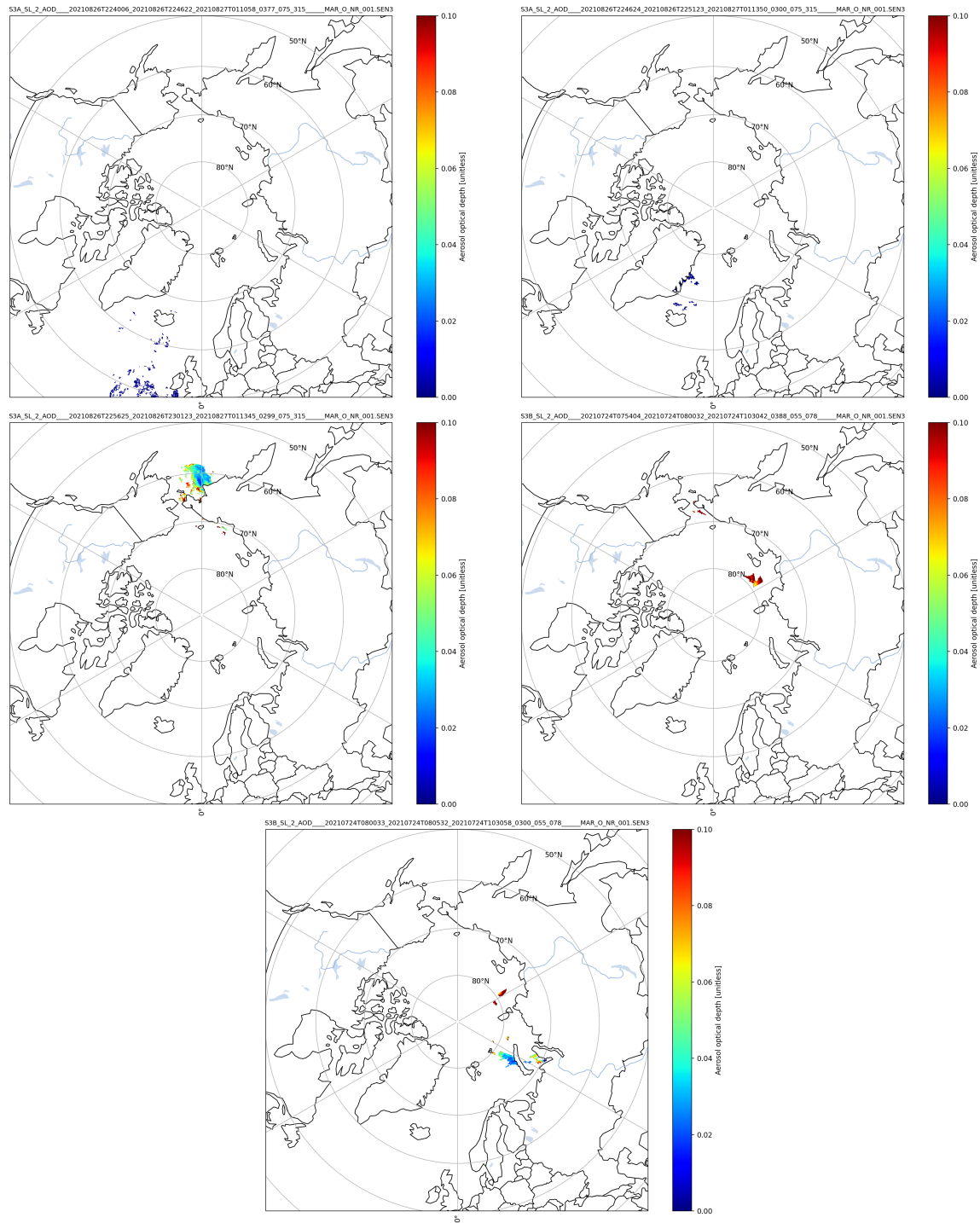


Figure 28: Aerosol optical depth at 550 nm from the SLSTR AOD product for 2018-2021 available from data.space.copernicus.eu.