AO11: Quantifying Biomass Burning Aerosol Contributions over Greenland using Satellite Observations

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Word Count: 3466

1 Abstract

In this study, data from the space based-lidar instrument Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) in combination with the passive instrument Moderate Resolution Imaging Spectroradiometer (MODIS) was used to analyse biomass-burning aerosols that are transported from Canada to Greenland. These aerosols are thought to be contributing to the melting of the Greenland ice sheet and wildfire smoke is increasing their impact. The occurrence of these aerosols over Greenland was shown to increase significantly during the summertime and a similar increase was shown in the aerosol optical depth (AOD) of the stratospheric smoke. Considering potential misclassifications between different aerosols a ten-day period in August of 2017 was studied. It was seen that smoke is contributing significantly more to the aerosol loading than all other aerosol types combined, and that vertical properties such as layer thickness and altitude have distinct variation in time and space. The AOD retrievals over higher latitudes were a significant improvement compared to passive satellite data, although CALIOP lacks the ability to show the transport of smoke over a flat area. This report illustrates that spaced-based lidar is crucial to be able to study smoke aerosols and evaluate their impact on the atmosphere.

2 Introduction

The melting of the Greenland ice sheet is one of the main contributors to rising sea levels, with approximately 200 Gt of ice melting per year [1]. Greenland is usually affected by smoke aerosols transported from North America, and these can impact the melting in two separate ways, either by being deposited on the surface and changing the albedo, or by their effect on the overall radiative balance of the atmosphere. For example, there is evidence that light-absorbing smoke aerosols, like black carbon, are reducing the albedo through their deposition on the ice sheet [2]. Currently the impact of aerosols on radiative balance is not well constrained, and different models can disagree about whether smoke aerosols have an overall cooling or warming effect [3].

A large source of these aerosols is biomass burning within Canada. The Canadian wildfire season has shown a trend of increased severity and duration [4], despite there being fewer fires overall thanks to more effective firefighting. Modelling suggests that climate change will increase the frequency of these fires and the area burned [5], which in turn may increase the aerosol loading over Greenland.

To be able to better understand the effects of these smoke aerosols, knowing the vertical distribution of them is crucial. The altitude of the aerosols impacts their direct radiative effect and their indirect radiative effect through cloud-aerosol interactions, which depends on their ability to function as cloud condensation nuclei (CCN) [6]. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite has an active lidar instrument, CALIOP, that offers a unique opportunity to study the vertical profile of the atmosphere over the globe.

This study uses CALIOP data to analyse these biomass burning aerosols and their transport to Greenland in the years 2008 - 2018. As well as looking at the seasonal variation, particular attention is given to the 2017 wildfires, which burnt a record area of 1.2 million Ha [7] in British Columbia. To confirm the origin and evolution of these aerosols, carbon monoxide data is used in combination with back trajectory modelling. Key factors of the vertical distribution: layer thickness, layer height and layer optical properties, are studied to evaluate their temporal and spatial variation. This kind of analysis is unique to CALIPSO as only ground-based lidar can make these measurements but they are highly limited in their spatial coverage. CALIOP aerosol optical depth (AOD) data is also compared with MODIS, a passive instrument that has significantly larger spatial coverage with a viewing swath of 2,330 km [8]. The MODIS platform follows the same orbital tracks as CALIPSO, making direct comparison possible.

3 Methods

3.1 General Methodology

An area of 120° to 10° West and 50° to 85° North was chosen to study; this included the main areas of wildfire burning but not the entirety of Canada. When dividing the data between the two countries, the two regions in Figure 1 were used. The ten-day period that was analysed more closely was from 2017/08/14 to 2017/08/23, this included the days with the highest amount of smoke occurrences in Canada, as shown in Appendix A, and increasing occurrences in Greenland. Occurrences in this report refer to the number of layers with aerosols identified by CALIOP.

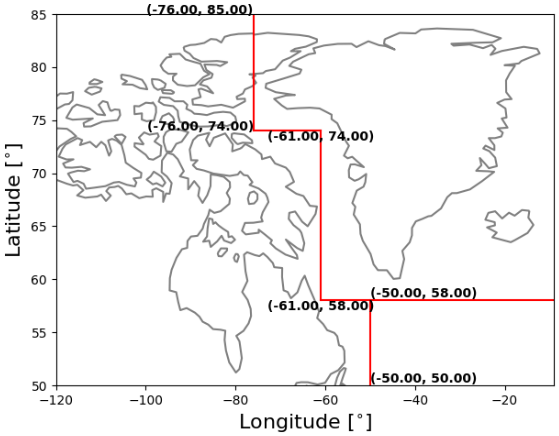


Figure 1: Boundary line used for dividing data between Canada and Greenland, left-hand side is Canada, the upper right is Greenland, and the lower right was discounted, exact coordinates are labelled on the map.

3.2 CALIOP Data

CALIOP works in two wavelengths, 532 nm and 1064 nm, all values used for this study were from the 532 nm channel as this is more accurately calibrated than the 1064 nm [9]. As CALIPSO has a sun-synchronous orbit, it's latitudinally limited to about 82.5° North, and has a vertical resolution of 30 m in the lower atmosphere which increases to 60 m above 8.2 km [10]. The data was taken from the CAL_LID_L2_05kmALay-Standard-V4-51 product, which does not contain retrievals from the full profile but just the layers of the atmosphere where aerosols were found. The CALIOP version 4.51 algorithm recognises 11 different aerosol subtypes, shown in Appendix B alongside the flowchart used to classify the tropospheric types. Each aerosol found by CALIPSO has a Cloud-Aerosol Discrimination (CAD) score; the sign of which indicates the feature type found (positive for cloud and negative for aerosol) and the absolute value gives the confidence interval that the classification is correct. For all analysis in this paper a CAD score of less than -20 was used as a reliable indication of an aerosol.

One issue with using layered data is that one profile can have multiple aerosol identified layers, those from the same profile were added together to get the total AOD. For calculating the extinction coefficient, the AOD of each layer was divided by the layer thickness in kilometres, taken as the difference between the top and base altitude, hence all values are in km^{-1}. To extract the average extinction coefficient, an atmospheric grid of 0.5° by 0.5 km was constructed and the sum of all of the values in a particular bin was divided by the total number of profiles in that latitude/longitude column. This accounted for what were essentially zero values of optical depth in between the layers. There are several periods where CALIOP doesn't have any data, these can range from a few days to an entire month. When looking at the monthly variation, the total number of aerosol occurrences was divided by the number of days with valid data, giving an unbiased daily average.

For looking at the seasonal variation it was assumed that all elevated smoke and stratospheric smoke from the CALIOP aerosol classification had a biomass-burning origin. The other smoke subtype, polluted continental/smoke, is a mixture between two different types and was not included. However, looking at the monthly variation of this subtype, in Appendix C, it can be seen that AOD increases as the occurrences decrease in the summer, this decrease may be due to CALIOP detecting polluted continental aerosols more during the nighttime. The increase in AOD suggests that during the summertime, this subtype is made up of significantly more smoke. Consequently, when analysing aerosols in the summer (June - August) this subtype was included.

When looking at the CALIOP profiles for the short time period in 2017, example in Figure 2, there was evidence of a misclassification between stratospheric smoke and sulphate/volcanic ash in the large stripy white plume. This misclassification comes from the fact that CALIOP assumes all smoke particles to be irregularly shaped, which is not the case for aged smoke particles that are spherical like sulphates and ash [11]. It's shown in Appendix C that the occurrences of sulphates and ash do increase during this summer due to this misclassification. As during this period there was no volcanic activity to produce the sulphates and ash, these were included as misclassified smoke aerosols. Similar stripes can be seen in black and orange, these are elevated smoke and polluted dust, respectively. However, this misclassification is less well documented, and has a potential source from Asian dust storms [12]. In Appendix C it can be seen how, like polluted continental/smoke, the AOD increases as the occurrences drop, suggesting that smoke is contributing more during the summer. Despite this, there was not enough evidence to include this as a biomass-burning aerosol so it was excluded. None of these subtypes were considered when looking at the seasonal variation.

3.3 IASI Data and HYSPLIT

To visualise aerosol transport during the wildfire event, the carbon monoxide (CO) product from the Infrared Atmospheric Sounding Interferometer (IASI) instrument aboard the Metop-B satellite was used. IASI works by measuring the infrared energy at the top of the atmosphere in many different spectral channels [13]. CO observations are a good proxy for aerosol transport [14], and IASI has the advantage of having higher spatial coverage than CALIPSO. Metop-B also has a sun synchronous orbit meaning it can't see into very high latitudes. To visualise the full path the smoke was taking, the Hybrid

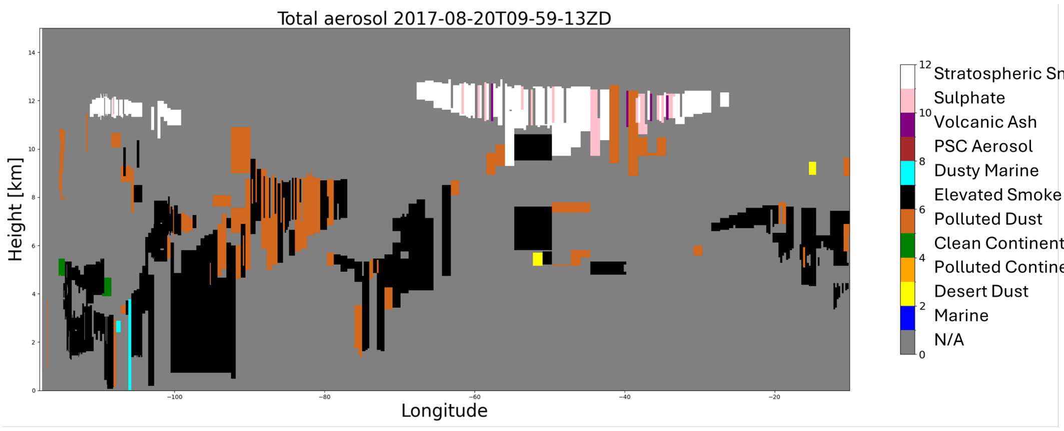


Figure 2: CALIOP Level 2 Aerosol Profile 2017/08/20, filename CAL_LID_L2_05kmAPro-Standard-V4-51.2017-08-20T09-59-13ZD.hdf.

Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) was used. This model combines Lagrangian and Eulerian methods, along with weather archives, to trace the air parcel trajectories [15]. The ensemble trajectory method was used for this modelling, which takes a given input point based on its latitude, longitude and altitude and deviates around it to create 27 possible trajectories. The input coordinate was chosen as a central point in a large plume of smoke.

3.4 MODIS Data

To be able to visualise where the wildfires were, the MODIS active fire product was used, with data downloaded from the FIRMS archive. Only temperature anomalies with 100 percent detection confidence were classed as active wildfires.

The MODIS MCD19A2 product combines data from the Terra and Aqua satellites for the AOD calculated in the 550 nm channel [16], this was used for comparison to CALIOP. There is a time delay between the measurements from Terra and Aqua, but this was deemed insignificant. As MODIS cannot distinguish between different aerosol types as well as CALIOP, all subtypes were considered from both datasets. To qualitatively compare the coverage and measurements of the instruments, the average AOD over the ten-day period was analysed. Only retrievals with an AOD above 0.2 were considered, as these are most likely to be induced by smoke. Analysing a single pair of observations, there can be temporal variability from the atmosphere and spatial variability from the observations, and it's not expected that the two measurements will agree. To check for this, average AOD values, aggregated in a 0.5° latitude and 0.5° longitude grid, were compared on particular days and the minimum AOD applied was varied to see how this impacted the average difference over all the days.

4 Results

4.1 Seasonal Variance

Looking at the monthly variation of the biomass burning aerosols over Greenland, Figure 3, there is a peak in the occurrences during August for the elevated and stratospheric smoke, and a large increase in the variance. This confirms that smoke aerosols are significantly more abundant during the summer. There is also more elevated smoke than stratospheric smoke, this is to be expected as above the tropopause there is no longer convective mixing and so less particles reach above this level. Interestingly there is no summertime peak in the AOD for the elevated smoke, despite it being clear in the stratosphere. This could possibly be to do with the misclassification between elevated smoke and dust, as there is no reason to believe this couldn't go both ways, however this not the case for the stratospheric misclassifications. As the smoke moves up the atmosphere, it's expected that the layers will thin out and the optical depth will decrease, this is confirmed as the stratospheric AOD is around a factor of 10 lower than the elevated smoke in a particular month.

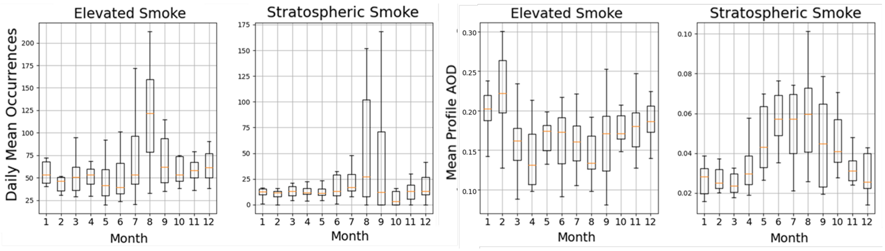


Figure 3: Box plot of the daily mean occurrences and average AOD by month for subtypes elevated and stratospheric smoke over Greenland from 2008 to 2018. The whiskers run no further than 1.5 times the interquartile range, so do not necessarily show the full data range.

4.2 Short Term Analysis

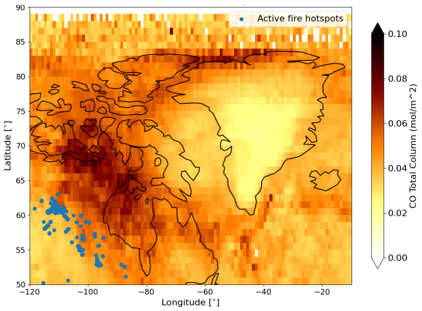
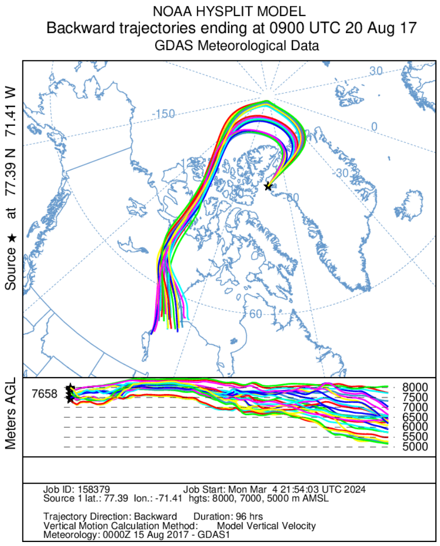


Figure 4: Mean carbon monoxide column amount, IASI, 2017/08/14 - 2017/08/23, blue dots show all the active fire hot spots during this period.

Figure 4 shows the CO observations during the short time period, and the transport of aerosols to the higher latitudes of Greenland is clearly illustrated. When looking at CALIOP occurrence data, in Appendix D alongside the orbital tracks, it does appear that there is significantly more smoke in the higher latitudes, however a full view of its horizontal coverage is limited by CALIPSO's narrow field-of-view. These CO measurements act as an independent check that this higher occurrence is a real feature of the data. The HYSPLIT plot, Figure 5, shows how the smoke moves quite far into the Arctic, before moving back down into Greenland, explaining the increased occurrences at the higher latitudes. The time for the smoke to make this journey is around 3 days, starting on the 17th and arriving on the morning of the 20th.



```
Job ID: 158379                    Job Start: Mon Mar  4 21:54:03 UTC 2024
Source 1 lat.: 77.39  lon.: -71.41  hgts: 8000, 7000, 5000 m AMSL

Trajectory Direction: Backward     Duration: 96 hrs
Vertical Motion Calculation Method:     Model Vertical Velocity
Meteorology: 0000Z 15 Aug 2017 - GDAS1
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Figure 5: HYSPLIT plot starting at 77.39°N 71.41°W on 2017/08/20, input heights are 8000 km , 7000 km and 5000 km [17].

The vertical distribution of the extinction coefficient, Figure 6, shows the smoke having a considerably higher impact on the aerosol loading than all other subtypes. The

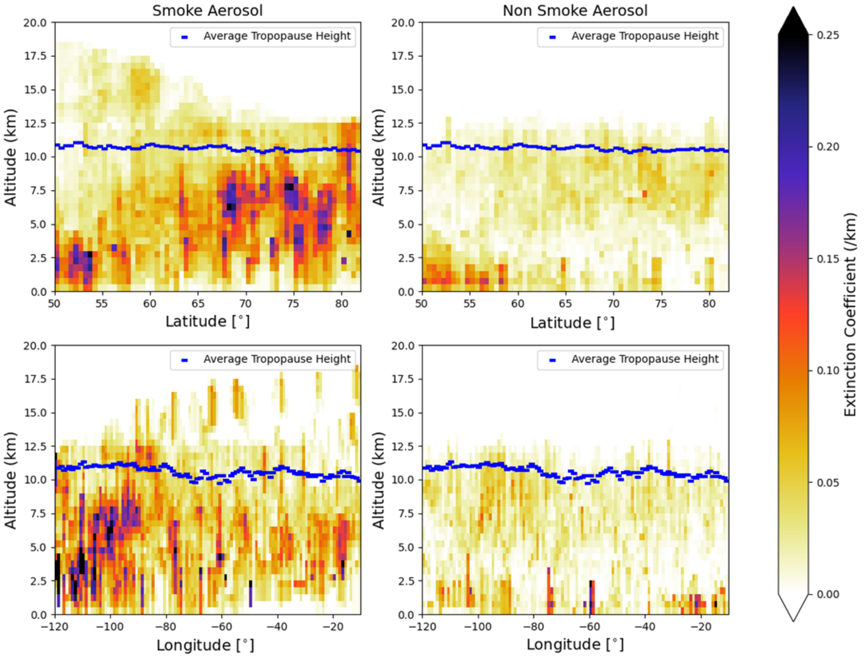

Figure 6: Average extinction coefficient 2017/08/14 - 2017/08/23, the top row is the latitudinal variation binned in 0.5° intervals and the bottom row is longitudinal variation binned in 1° intervals. The altitude is binned in 0.5 km intervals and the average tropopause height is based on the troposphere height for all aerosols over the whole period.

longitudinal variation of the smoke shows a clear lifting from the main wildfire locations, around 110° W, up and across to Greenland. It also shows smoke is entering the stratosphere close to the source and moving across, rather than lifting above the tropopause later in the transport. The mixing of the aerosols appears to continue around a kilometre after the tropopause height, CALIOP gets this height from the MERRA-2 model [10] and values were averaged for all aerosols. Interestingly, the vertical distribution for the non smoke aerosols appears to banded, with a significant drop in extinction coefficient around 5 km. This could be due to smoke dominating the backscattered signals when there's a mix of different aerosols.

Figure 7 illustrates the evolution of the layer and profile properties of the smoke through the ten-day period, divided between Greenland and Canada. The numbers of layers/profiles show around a three-day delay between the increase in smoke being emitted and reaching Greenland. This matches what was seen in the earlier HYSPLIT plot and shows the majority of the smoke is taking that same delayed route into the upper Arctic before it comes back down South. Prior to the 18th significantly less smoke was seen in Greenland, this means the derived properties for these days are statistically less significant.

In Canada, there is a higher increase in the number of smoke layers compared to that of the profiles starting on the 20th; this could suggest that the smoke emitted on previous days is horizontally spreading in the atmosphere. This would also explain the rapid decrease in the upper whiskers of the AOD at the same time and there is a corresponding slight decrease in the layer thickness. The altitude range of smoke layers is higher in Canada, the average being 12 km compared to 10 km in Greenland, like seen in the ex-

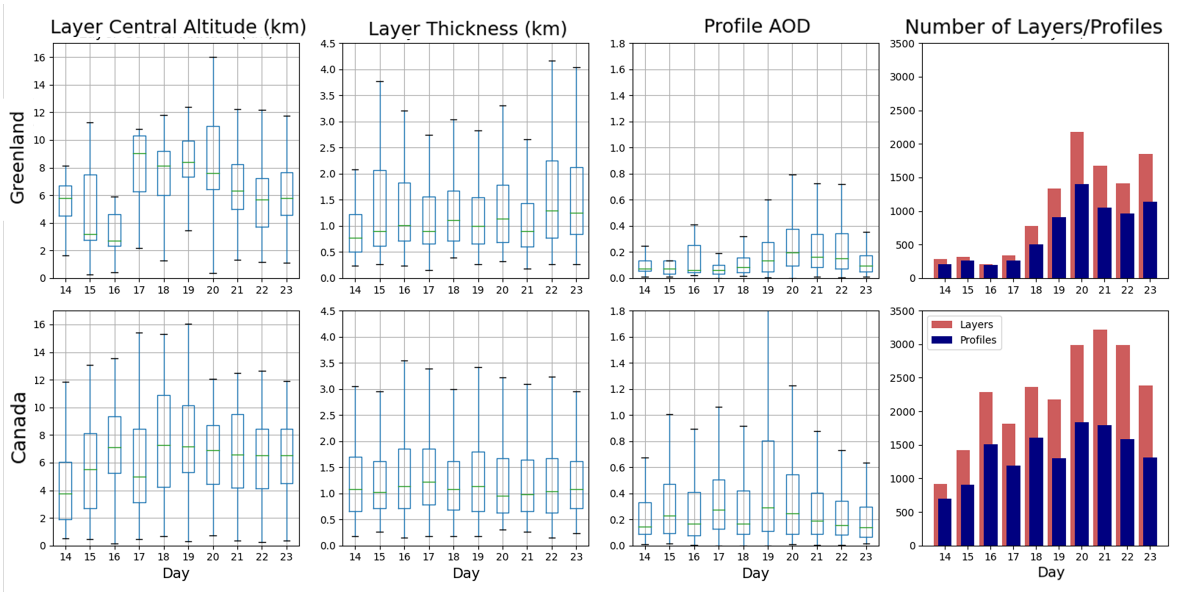

Figure 7: Box plots showing from left to right: Layer central altitude (km), Layer thickness (km), Profile AOD, Number of Layers/Profiles, for each day in the period 2017/08/14 - 2017/08/23, the top row is Greenland and the bottom is Canada. The whiskers run no further than 1.5 times the interquartile range, so do not necessarily show the full data range.

tinction coefficient there is more smoke in the stratospheric altitudes and more at the surface where it is being emitted. However, for some days in Greenland the whiskers do extend all the way to the surface, suggesting that smoke is being deposited on the ice. The number of layers is closer to the number of profiles in Greenland, especially before the 19th, which also suggests a lower altitude variation in the smoke. There does appear to be a lower limit to the layer thickness, around 0.2 km, and the mean and variance are more consistent in Canada. Although the upper whiskers of the AOD in Canada are significantly higher than in Greenland, their means are more similar suggesting that the AOD doesn't decrease significantly during the transport, with the highest difference being around 0.3.

Figure 8 shows the MODIS and CALIOP latitude - longitude dependence of the AOD. The first thing to notice is the lack of MODIS data in the higher latitudes of Greenland. As a passive instrument it struggles to distinguish cloud from surface reflectance, meaning an ice sheet is expected to be challenging. Because its coverage is limited it's missing the area where most of the smoke is entering. CALIOP can see these higher latitudes, but because its spatial coverage is small it's missing aerosols in the main area of Greenland. Hence it's good that for this analysis, most of the smoke was in the higher latitudes or little would have been picked up by CALIOP. In the MODIS data the transport of the smoke is very clear, the purple lines are most likely one large plume that is being captured on different days. Whereas for CALIOP, this transport isn't visible, only the fact that there are more aerosols over Canada than in Greenland.

Directly comparing the average AOD values on particular days, Figure 9 shows how the mean difference changes with the minimum value used. It can be seen how for lower cut offs, the CALIOP AOD is higher than

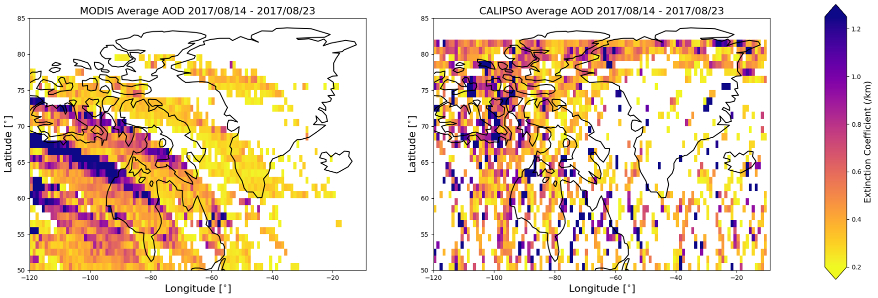

Figure 8: Average AOD values 2017/08/14 - 2017/08/23, excluding retrievals with values of AOD below 0.2, plotted in 0.5° by 0.5° latitude-longitude bins, left-hand side is MODIS and right-hand side is CALIOP.

MODIS, reflecting the fact that the MODIS instrument has more passes over a particular area in one day, and hence is biased by lower values where no smoke was present. However, once the cut off passes around 0.35, the MODIS values are now higher reaching a difference of 0.055 at an AOD cutoff of 0.8. This suggests that once the bias is removed, CALIOP actually underestimates the total AOD of the atmosphere, and that there is a systematic difference between the two measurements. This is common problem and can be due to CALIOP missing thin aerosol layers that are below the detection limit [18], or because it is unable to penetrate thick aerosol layers and missing information from the base layer. The lidar-ratio used also affects the extinction retrievals, so a biased ratio can impact the AOD calculated. It's important to note that most of these measurements will be reflecting those taken over Canada, so this doesn't necessarily reflect a difference over ice specifically.

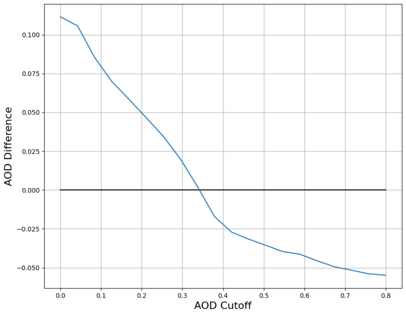

Figure 9: Average difference between CALIOP and MODIS daily AOD from 2017/08/14 to 2017/08/23, against the minimum AOD.

5 Conclusions

CALIOP aerosol data has been used to analyse smoke over Greenland from 2008 to 2018, as well as smoke transport from the 2017 Canadian wildfires, alongside MODIS aerosol data, IASI CO data and back trajectory modelling. A significant summertime increase in the occurrence of smoke aerosols in Greenland has been shown, however, it is not necessarily matched by an increase in the optical depth of the smoke, this could potentially be due to misclassification issues. There are more effective ways of showing the transport of smoke than CALIOP data, like IASI CO data or MODIS AOD data, although the latter is much less effective over the ice sheet. CALIOP is useful for looking at the vertical transport of smoke through the distribution of the extinction coefficient, especially where particles may be entering the stratosphere. This distribution also allows comparison between the aerosol loading of smoke and non-smoke aerosols, which during peak wildfires was shown to be significantly higher for the former. Due to the pattern of the orbital tracks, CALIOP retrievals are more frequent over higher latitudes in the Northern hemisphere. This can actually be very useful as this is an area where detection can be difficult, as shown with MODIS, but is something that needs to be carefully considered when looking over a landmass with a high latitudinal range like Greenland.

Looking at the vertical distribution of the aerosol properties, after the smoke has been transported the layer thickness shows increased variation and the number of layers within a profile decreases. The central altitude of aerosol layers over Greenland suggests that some of the smoke is being deposited on the surface; further work would consider the uncertainties in the CALIOP measurements when calculating these properties. Another important step would be to reduce the uncertainties in the misclassifications, this could be achieved by looking at the wavelength dependence of properties like the backscatter coefficient and the extinction coefficient [11]. Currently, only ground lidar work in sufficiently different wavelengths to have varying dependencies for smoke aerosols, so the area of this analysis would be limited. The CALIPSO satellite has now stopped working, as of August 2023, but there will be a new lidar launched by ESA in May 2024 called ATLID aboard the EarthCARE satellite [19]. Combining space-based lidar measurements from multiple wavelengths could allow for clearer classifications and would greatly help this kind of analysis. In conclusion, smoke analysis has been achieved by combining space-based lidar data with data from multiple other satellites, and has shown that biomass-burning aerosols are contributing significantly to the aerosol loading over Greenland in the summertime.

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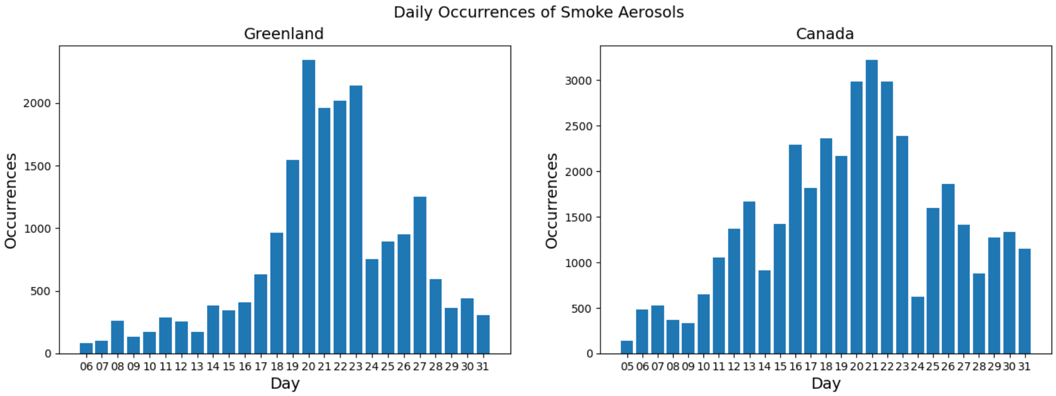
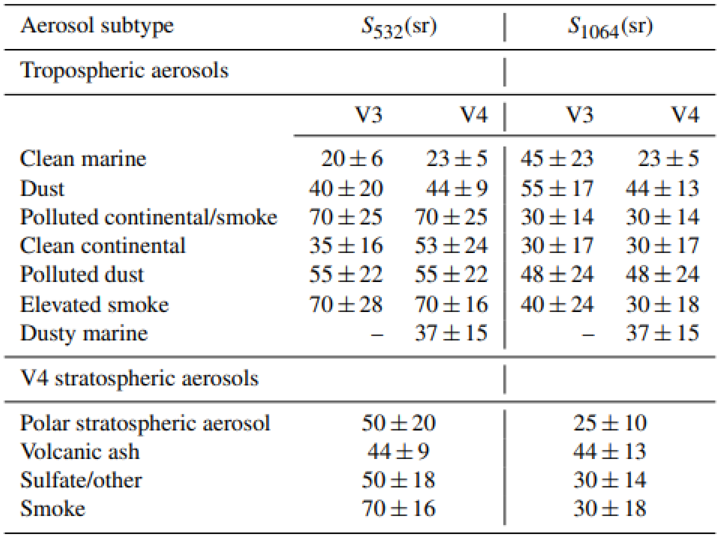
Appendices

A



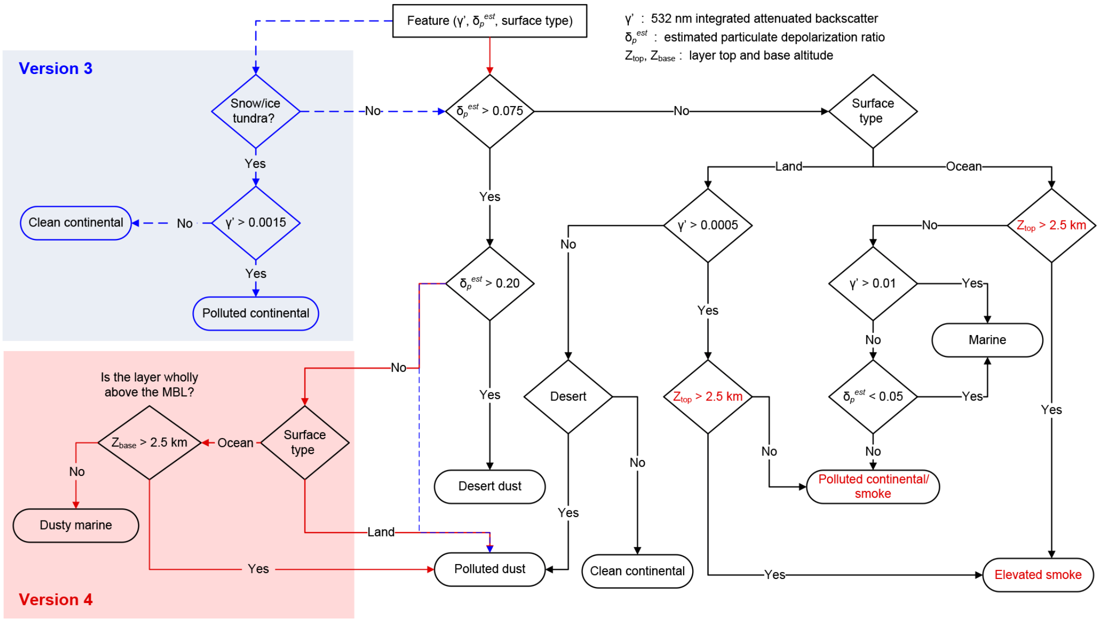
Smoke occurrences in Canada and Greenland through the month of August 2017, data begins at 2017/08/05 due to lack of CALIOP data before this.

B



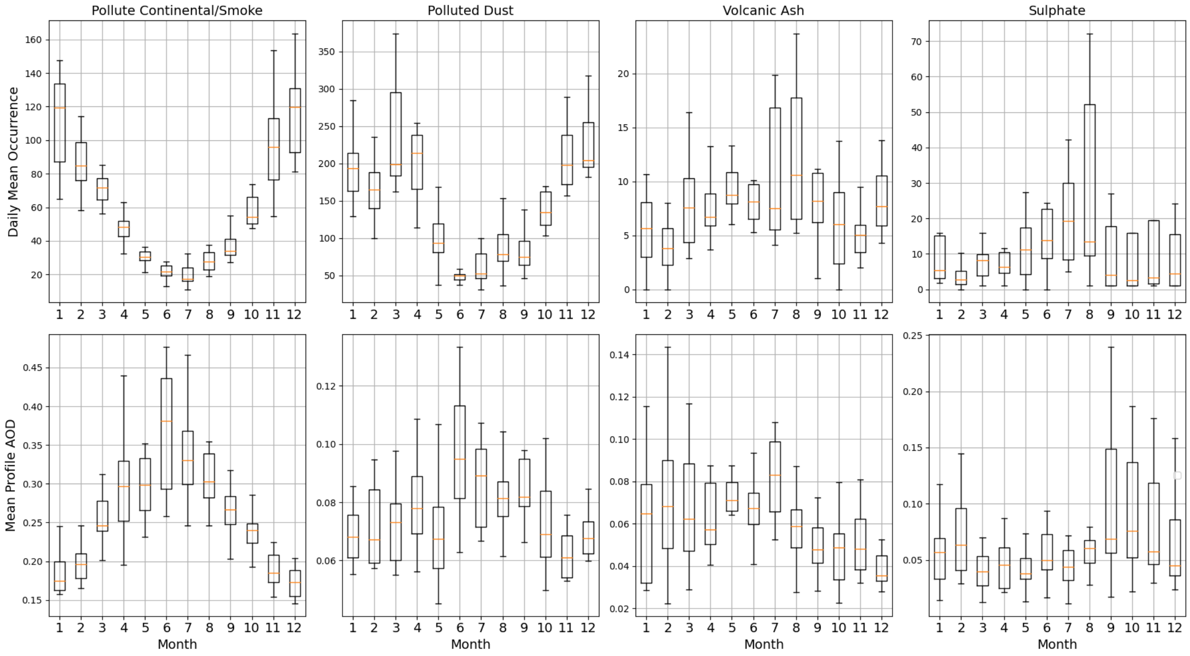
Aerosol subtype	S_{532}(sr)		S_{1064}(sr)	
Tropospheric aerosols				
	V3	V4	V3	V4
Clean marine	20 ± 6	23 ± 5	45 ± 23	23 ± 5
Dust	40 ± 20	44 ± 9	55 ± 17	44 ± 13
Polluted continental/smoke	70 ± 25	70 ± 25	30 ± 14	30 ± 14
Clean continental	35 ± 16	53 ± 24	30 ± 17	30 ± 17
Polluted dust	55 ± 22	55 ± 22	48 ± 24	48 ± 24
Elevated smoke	70 ± 28	70 ± 16	40 ± 24	30 ± 18
Dusty marine	–	37 ± 15	–	37 ± 15
V4 stratospheric aerosols				
Polar stratospheric aerosol	50 ± 20		25 ± 10	
Volcanic ash	44 ± 9		44 ± 13	
Sulfate/other	50 ± 18		30 ± 14	
Smoke	70 ± 16		30 ± 18	

Aerosol lidar ratios used for the subtypes by CALIPSO, table lists both version 3 and version 4 [12].



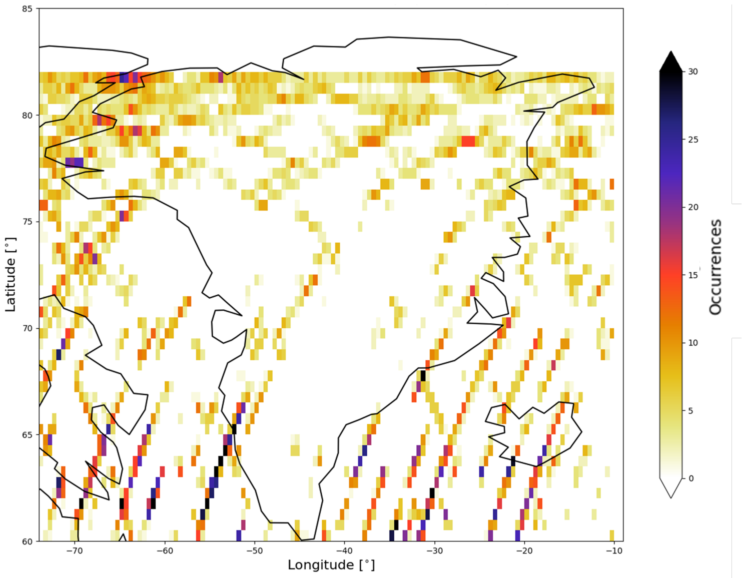
CALIPSO flowchart for tropospheric subtypes, upper right blue box shows old classification system for version 3 [12].

C

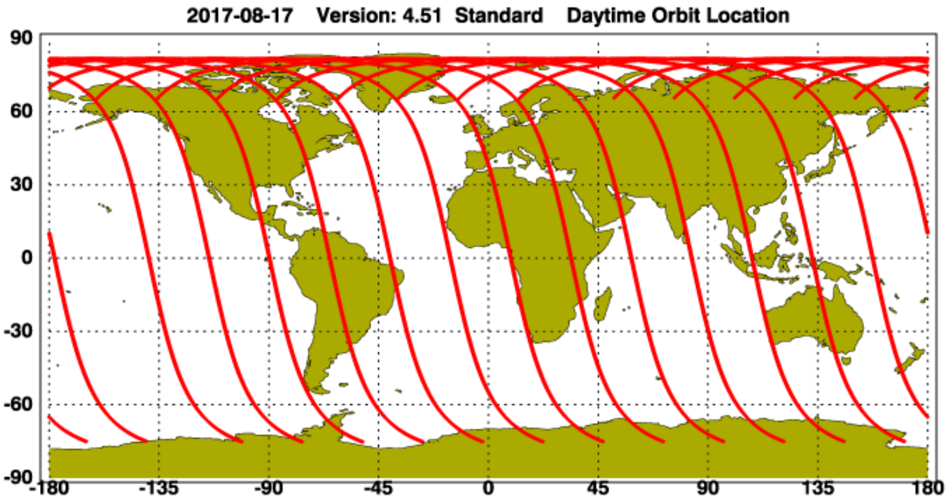


Box plot of the daily mean occurrences and average AOD by month for subtypes polluted continental/smoke, polluted dust, volcanic ash and sulphate over Greenland from 2008 to 2018. The whiskers run no further than 1.5 times the interquartile range, so do not necessarily show the full data range.

D



Total smoke occurrences around Greenland from 2017/08/14 - 2017/08/23, plotted latitude versus longitude in 0.5° bins.



Example of CALIPSO orbital tracks on 2017/08/17, taken from `https://www-calipso.larc.nasa.gov/products/lidar/browse_images/std_v451_index.php?d=2017`, accessed 2024/03/14.