Author's response to reviewer number 1

AC: We thank the anonymous referee for the detailed review of our manuscript. We carefully reviewed each comment and have amended at manuscript to address the issues raised. Reviewer comments are in black with our responses in blue. Changes to the manuscript are in the small font size 10.

RC1: General major comment.

While I think that the current title is fine, I believe that it does not highlight some of the more important results from this study. In my opinion, the more important points are two: 1) it unequivocally demonstrates with observations that high latitude dust activity can be very frequent and abundant 2) that existing mainstream instrumentation such as satellite and Aeronet can miss significantly a number of events and demonstrate they are not suitable for a climatological studies. I think these two facts are more relevant and of importance from the view of incorporating HLD in global surveys and modelling efforts.

AC: We thank the reviewer for this comment. To address your concerns we have retitled the paper, "The (mis)identification of high latitude dust events using remote sensing methods in the Yukon, Canada: A sub daily variability analysis". We hope this is satisfactory.

RC1: In addition, this study demonstrates something that was already reported in the Urban et al and Baddock et al (cited) papers where they excellently demonstrate how modern polar satellites very often miss dust activity to the point that it is clearly undercounting a significant amount of events. As a result, global assessments that rely in satellite data are biased towards lower latitudes. This study further contributes to this concept with the novelty that this is a largely unknown dust activity regime at latitudes not considered in the above studies.

AC: Thank you for your valuable comments and suggestions. Please find our answers to the individual specific comments below.

RC1: Overall comments about satellite images. I read this manuscript in a printed version of the paper. All satellite images (except perhaps figure 2) had poor contrast and the darks were too dark and without definition. I can't tell if it was a problem in my printer, but this is a fact you may want to check before final submission. The PDF in the computer screen looked much better than in print.

AC: We thank the reviewer for this comment. We printed off and reviewed the satellite images and deemed the contrast are okay. We hope this is satisfactory.

RC1: Abstract:

It would be desirable to add information of the periods of time (months/years) of the surveys.

Overall the abstract highlights too much the technical aspect of detecting of changes thresholds and does not report a more important fact: dust activity is much more frequent than previously expected and this project has quantified it. So for example, stating here what frequency was measured with the remote cameras and by Aeronet is a very important fact in my opinion.

AC: We thank the reviewer for this comment and agree. We have updated the abstract so that it now reads:

"The observation and quantification of mineral dust fluxes from high-latitude sources remains difficult due to a known paucity of year-round in situ observations and known limitations of satellite remote sensing data (e.g., cloud cover and dust detection). Here we explore the chronology of dust emissions at a known and instrumented high-latitude dust source: Lhù'ààn Mân (Kluane Lake) in Yukon, Canada. At this location we use oblique time-lapse (RC) cameras as a baseline for analysis of aerosol retrievals from in situ metrological data, AERONET, and co-incident MODIS MAIAC to (i) investigate the daily to annual chronology of dust emissions recorded by these instrumental and remote sensing methods (at timescales ranging from minutes to years), and (ii) use data intercomparisons to comment on the principal factors that control the detection of dust in each case.

Lhù'ààn Mân is a prolific mineral dust source; on the 24/05/2018 the RC captured dust in motion throughout the entire day, with the longest dust-free period lasting only 30 minutes. When compared with time series of RC data, optimised AERONET data only manage an overall 26 % detection rate for events (sub day) but 100% detection rate for dust event days (DED) when dust was within the field of view. Here, in this instance, RC and remote sensing data were able to suggest that the low event detection rate was attributed to fundamental variations in dust advection trajectory, dust plume height, and inherent restrictions in sun angle at high-latitudes. Working with a time series of optimised AOD data (covering 2018/2019), we were able to investigate the gross impacts of DQ choice on DED detection at the month/year scale. Relative to ground observations, AERONET's DQ2.0 cloud screening algorithm may remove as much as 97 % of known dust events (3% detection). Finally, when undertaking an AOD comparison for DED and non-DED retrievals, we find that cloud screening of MODIS/AERONET lead to a combined low sample of co-incident dust events, and weak correlations between retrievals. Our results quantify and explain the extent of under-representation of dust in both ground and space remote sensing method; a factor which impacts on the effective calibration and validation of global climate and dust models."

RC1: Figure 1. Some of the stations in easter Patagonia are high latitude and do report both proglacial and depression dust activity so they should be tagged in pink. If I recall correctly the Neuquen, Comodoro Rivadavia and Rio Gallegos sites are such cases .

AC: Thank you for your comment, the original criteria for defining the HLMA stations was that the station had to be within 10 km of a glacier or any ice. This was rethought to add some leniency (to include most stations within ≥ 50 °N and ≥ 40 °S latitude) and as a result Comodoro, Neuquen, Rio Gallegos, and other AERONET stations were added. The figure has been modified, numbers updated, and projection corrected.

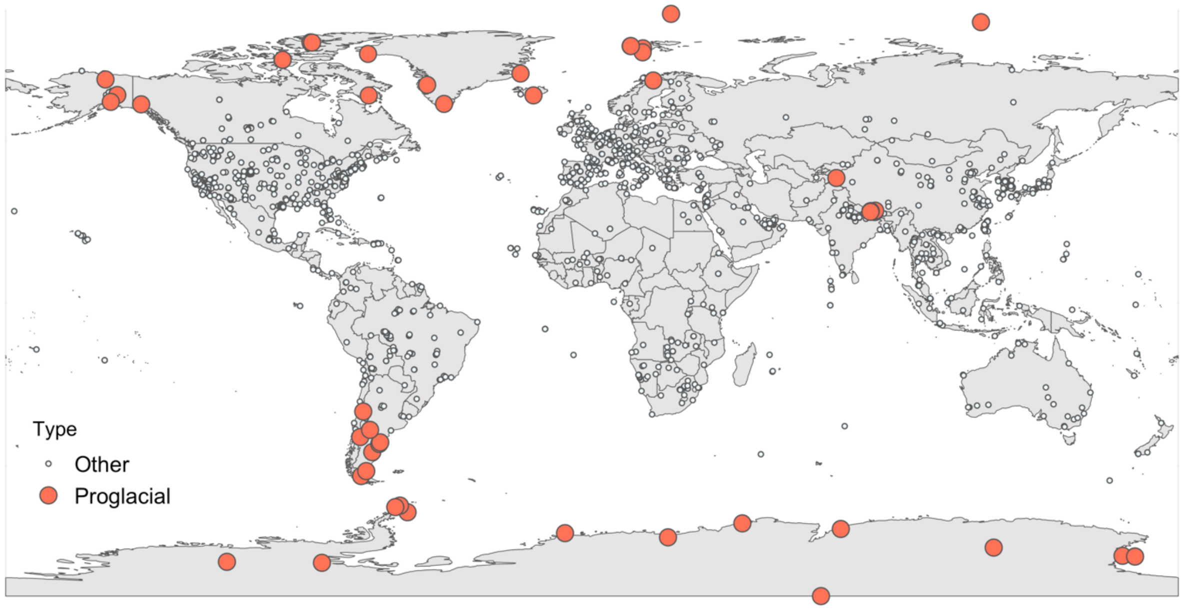


Figure 1. Location of all AERONET stations with stations in the high-latitudes or proglacial areas highlighted in orange. Cryospheric stations account for 48 out of 1655 global AERONET (data from the AREONET website: https://aeronet.gsfc.nasa.gov).

RC1: Figure 2: can you add the location of Burwash landing?

AC: The authors agree that adding Burwash Landing would provide important contextual data. However, this would require us to extend the map another 30kms to the north which may reduce the clarity of this figure in displaying where the instruments are in relation to the dust source area. Burwash Landing can been seen in Figure S1. We hope that this is sufficient.

RC1: Line 202 : The Aeronet … is a FEDERATED network ….

AC: This comment was considered and added to the manuscript. Thank you for the suggestion. The manuscript now reads:

"The AERONET (Aerosol Robotic Network; Holben, 1998) is a federated network of ground-based sun photometers that measure the rate of solar ray extinction in the atmospheric column above the photometer to determine AOD alongside other atmospheric properties."

RC1: Line 209-2010: add year of operation for those months.

AC: Agreed. The manuscript now reads:

"The Kluane Lake AERONET station (see Figure 2 and S1 for location) recorded data from early May to late October in 2018, 2019, 2020, and 2021."

RC1: Line 212 : "...and marine" , really marine aerosol here? it does not make sense to even mention this. Probably you are referring to the optically based aerosols models that can be distinguished with Aeronet. But the way this is phrased, it sounds like these aerosols are present.

AC: We thank the reviewer for highlighting this issue. The authors agree that this is confusing as the KLRS is far from the ocean. The Verma et al., (2015) threshold used here was for broad characterisation of the aerosols at the site and has been used in other scholarly articles for helping define thresholds (e.g., Bibi et al., 2016; Djossou et al., 2018; Iftikhar et al., 2018; Léon et al., 2021; Platero et al., 2018; Singh et al., 2020) . As HLMA is understudied, particularly using AERONET data, little to no thresholds had previously been defined. Therefore, the threshold of Verma et al., (2015) were used to broadly characterise what was happening at the site. Under this classification marine aerosols are present at the site, these maybe be due to clouds or other arid background aerosols at the site. Therefore, the authors have removed this mention of "marine aerosols" and added in a comment regard the use of this threshold later in the manuscript regarding this issue. The manuscript now reads:

"In this study, the likely presence of dust events was determined through use of initial generic thresholds at two different AERONET wavelengths, 500 nm and 1020 nm. Thresholds at 500 nm were used to broadly characterise aerosols at Lhù'ààn Mân with thresholds used in arid environments (Verma et al, 2015). Therefore, whilst the 500 nm definitions are useful to understand the aerosol environment at KLRS, it may not be truly representative of dust emissions. This is evident when compared to direct ground data observations, AERONET-derived dust events in this study recorded at longer wavelengths were found to be a closer match to the known frequency of events than those at shorter wavelengths (Figure 9ab). For example, on a day where RC data shows dust events for 95.8% of the day (24th May 2018), 11.6% of AOD readings were classified as dust using the thresholds from Verma et al. (2015), whereas thresholds from Dubovik et al. (2002) yielded 24.2% AOD readings as dust. We, therefore, note that careful consideration in wavelength and definition thresholds is needed when quantifying HLMA in AERONET data." [Lines 500-511]

We hope this is satisfactory.

Ref.: Bibi, H., Alam, K., and Bibi, S.: In-depth discrimination of aerosol types using multiple clustering techniques over four locations in Indo-Gangetic plains, Atmos. Res., 181, 106–114, https://doi.org/10.1016/j.atmosres.2016.06.017, 2016.

Djossou, J., Léon, J. F., Barthélemy Akpo, A., Liousse, C., Yoboué, V., Bedou, M., Bodjrenou, M., Chiron, C., Galy-Lacaux, C., Gardrat, E., Abbey, M., Keita, S., Bahino, J., N'Datchoh, E. T., Ossohou, M., and Awanou, C. N.: Mass concentration, optical depth and carbon composition of particulate matter in the major southern West African cities of Cotonou (Benin) and Abidjan (Côte d'Ivoire), Atmos. Chem. Phys., 18, 6275–6291, https://doi.org/10.5194/acp-18-6275-2018, 2018.

Iftikhar, M., Alam, K., Sorooshian, A., Syed, W. A., Bibi, S., and Bibi, H.: Contrasting aerosol optical and radiative properties between dust and urban haze episodes in megacities of Pakistan, Atmos. Environ., 173, 157–172, https://doi.org/10.1016/j.atmosenv.2017.11.011, 2018.

Léon, J. F., Barthélémy Akpo, A., Bedou, M., Djossou, J., Bodjrenou, M., Yoboué, V., and Liousse, C.:

PM2.5surface concentrations in southern West African urban areas based on sun photometer and satellite observations, Atmos. Chem. Phys., 21, 1815–1834, https://doi.org/10.5194/acp-21-1815-2021, 2021.

Platero, I. Y., Estevan, R., Moya, A., and Yuli, R. A.: Determining the desert dust aerosol presence in the Mantaro Valley, Peru, Opt. Pura y Apl., 51, 1–14, https://doi.org/10.7149/OPA.51.3.50023, 2018.

Singh, P., Vaishya, A., Rastogi, S., and Babu, S. S.: Seasonal heterogeneity in aerosol optical properties over the subtropical humid region of northern India, J. Atmos. Solar-Terrestrial Phys., 201, 105246, https://doi.org/10.1016/j.jastp.2020.105246, 2020.

RC1: Figure 4: can you place location of video cameras in this figure?

AC: We thank the reviewer for this suggestion. The authors agree that this would aid with the readability of the figure. The locations of the video cameras were added to figure 3 &4 in the manuscript.

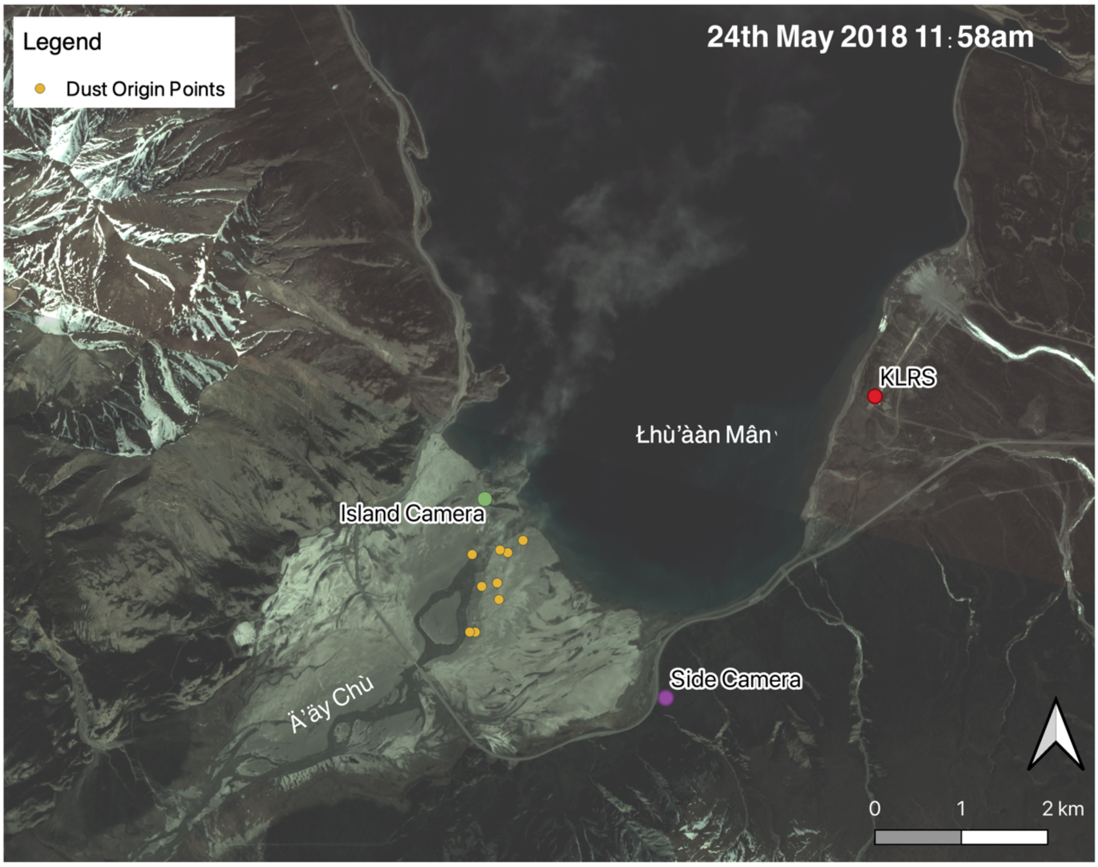


Figure 4. Image shows the plume rising from the Á’áy Chù delta and going out across the lake captured by PlanetScope (24th May 2018 at 11:58 am local time) overlaid point dust source locations (PDS). Due to the high resolution of the PlanetScope imagery (c. 3 m) we were able to trace the plume to the up-valley source on the delta. The Kluane Lake Research Station’s position is identified in red (KLRS), with the RC side camera identified in purple and the island camera in green.

RC1: Table 2 is not referenced anywhere in the text. With respect MAIAC data, you could add the collection or version of the MAIAC algorithm.

AC: Thank you. Table 2 in now referenced throughout the text. The authors agree that the MAIAC version should be included, and it has been added to the manuscript.

Table 2. Spectral bands and data quality of spectral data used in this study

Spectral Data Used	Wavelength	AERONET Data Quality Level	Application
AERONET AOD (AOD_D)	1020 nm	1	Determination of DEDs
AERONET AOD (AOD_A)	500 nm	1	Comparison against other aerosol types in air column Comparison against MODIS MAIAC
AERONET Angström exponent (α)	440-870 nm	1	Determination of DEDs
AERONET SSA	440, 675, 870, and 1020 nm	2	Radiation scattering effectiveness of aerosols
AERONET Volume Size Distribution	340, 380, 440, 500, 675, 870, 1020, and 1640 nm	2	The percentage of spherical particles in the observed aerosol to determine peaks in particle size
MODIS MAIAC (MCD19A2 V6.1) Land Aerosol Optical Depth Daily 1km (AOD_M)	470 nm	n/a	Space-based AOD estimates

RC1: 4.1 Event scale Observations. Can you please provide rough numerical estimate of the tops of the dust plumes? are we talking about tens of meters? a few hundred meters height? this is useful for contextual information.

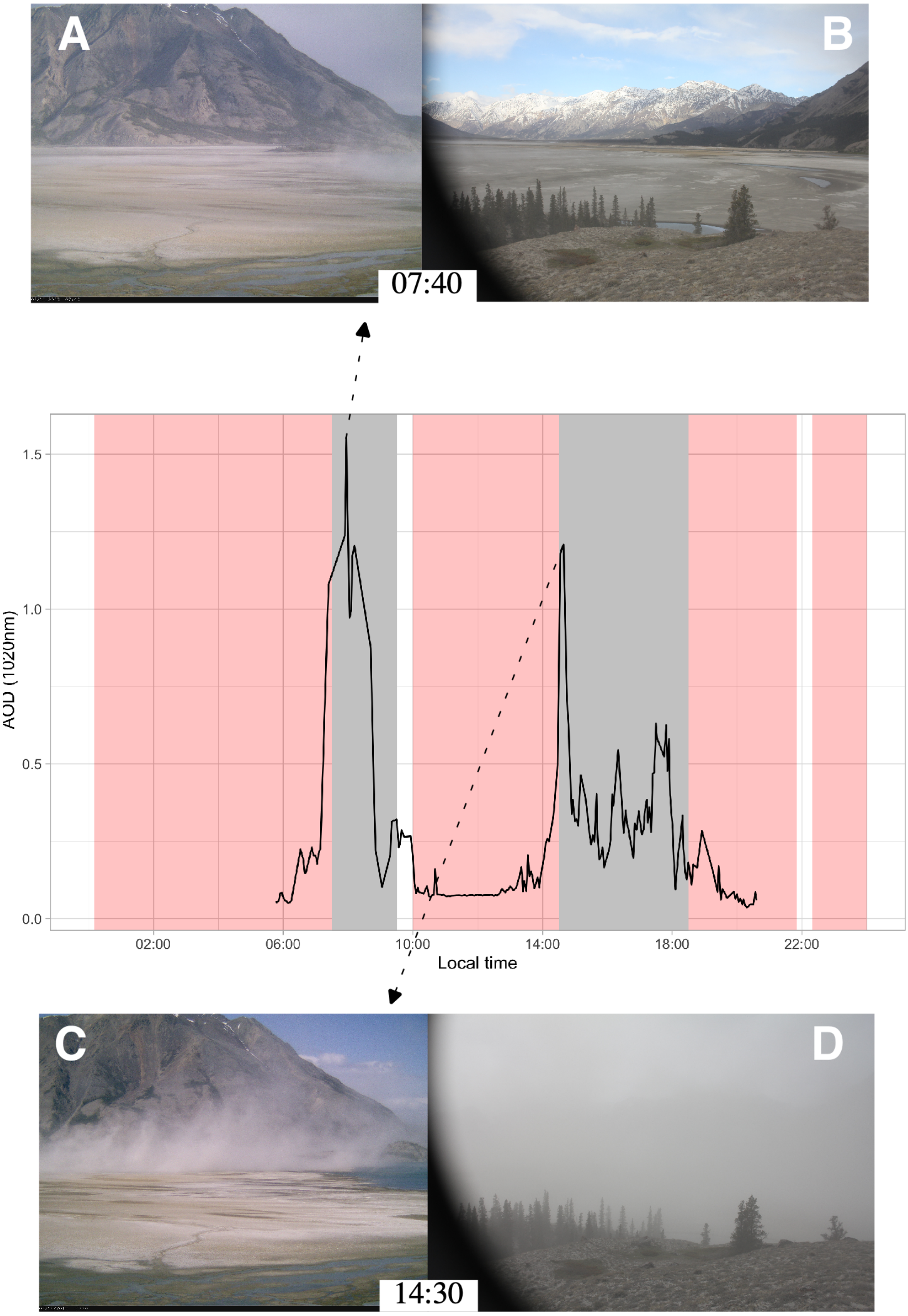
AC: Thank you. Although not data analysed here, a lidar was installed in May 2019 at KLRS by co-authors (and the LiDAR is co-located with the AERONET station that we use here) and regularly sees plumes at or exceeding 500 m and in larger events exceeding 1 km.

RC1: Figure 6. This is a nice and informative figure. But what is the purpose of the labels a,b,c and d if they are not referenced in the text?

AC: We thank the reviewer for this suggestion. The authors agree with this comment and the labels are now referenced carefully throughout the text.

RC1: Also, please make clear in the x-axis that it is local time.

AC: We thank the reviewer for this suggestion. The authors agree that to make this figure more accessible an addition of local time was necessary. A revised version has been added to the manuscript.



RC1: Perhaps you could add in one of the mountain slopes a reference height to compare with the dust cloud? Also, the distance from cameras to mountain visible across the valley would be useful information.

AC: We thank the reviewer for this suggestion. The distance to the mountain from the side camera is ~5 km and the elevation of the small peak at the top-centre of the image frame is 1910 m asl or roughly 1100 m above the lake surface. As for the island camera, this is more challenging as the background is not as close. The closest set of mountains on the right of the frame that are snow-capped are 14 km away and 2270 m asl. Information covering these points has now been added to the manuscript in the figure 6 caption. The manuscript now reads:

"Figure 6. AOD_D returns from the 24/05/2018 visualised with the corresponding oblique camera images during peak events. In the morning dust is in the southern section of delta. The distance to the mountain from the side camera (panels A&C) is ~5 km and the elevation of the small peak at the top-centre of the image frame is roughly 1100 m above the lake surface. As for the island camera (panels B&D), the closest set of mountains on the right of the frame that are snow-capped are 14 km away and 2270 m asl."

RC1: Line 359 - I found this reasoning difficult to follow because I could not see well in the images the camera locations.

AC: We thank the reviewer for this suggestion. The authors have updated the figures 3, 4, and 6 in order to clarify and better explain the camera locations in context with the dust source. See above for figures 4 and 6, figure 3 is updated below.

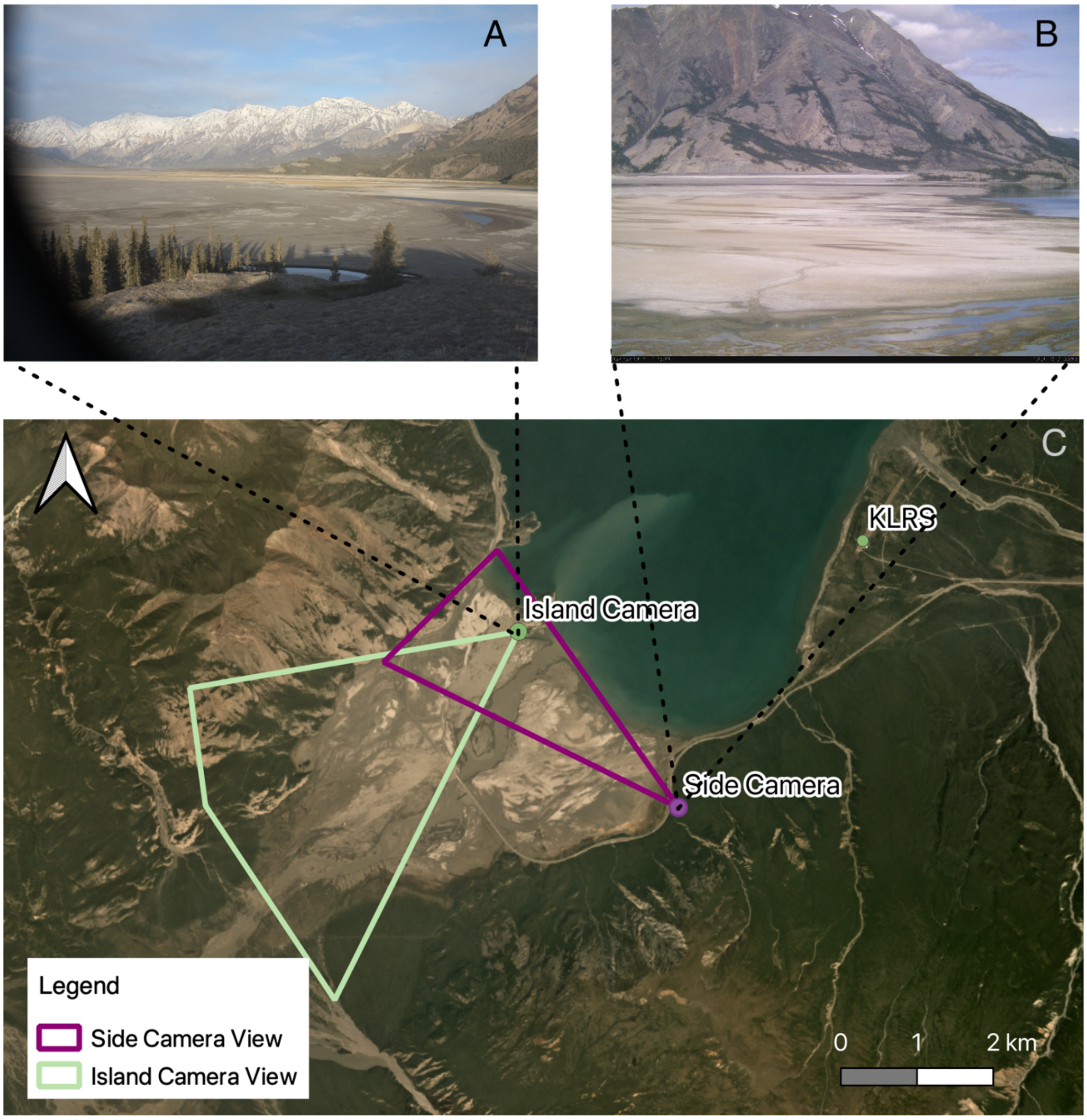


Figure 3. Locations of the oblique cameras and their approximate fields of view (3C). The Island camera in green is located on the former island in the delta looking south-west (3A). The Side camera is located near the Alaskan Highway looking north-west. Images so dust free views of the cameras (3B). Base imagery is from PlanetScope imagery in June 2018.

RC1: Line 400-404 I think it should be mentioned here the number of clear/cloudy days that Aeronet observed the Sun and how many of those dust was observed.

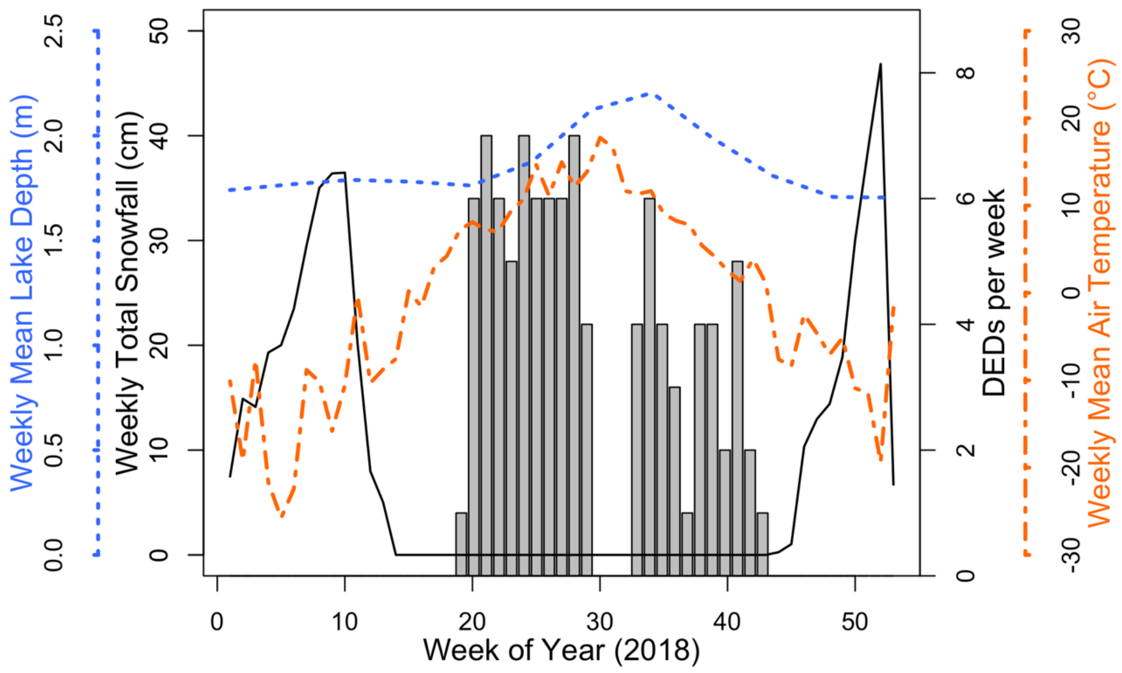
AC: We thank the reviewer for this suggestion. Due to the high latitude and mountainous area this site is situated in, it inevitably experiences a high amount of coincidence cloudy days. It would be hard to verify specific cloud impacts to a high-level of certainty, however, the authors have gone through MODIS Terra imagery and have added information on cloudy days for this daily overpass period to the supplementary information (Table S1).

Table S1. Dust event days and cloudy days at Lhù'ààn Mân over the study period. Cloudy days were decerned by analysing MODIS Terra images and DED decerned using 1020 nm wavelength from Dubovik et al. (2002).

	No. of cloudy days in month	No. of DEDs	No. of coincident DEDs and cloudy days
May-18	24	17	14
Jun-18	23	26	20
Jul-18	21	17	13
Aug-18	24	13	17
Sep-18	17	13	9
Oct-18	24	10	10
May-19	24	19	15
Jun-19	28	20	19
Jul-19	31	17	17
Aug-19	28	20	19
Sep-19	16	15	9
Oct-19	5	1	0

RC1: Figure 8 Caption. The description is a bit difficult to read. Are the vertical bars the DED/week? Also, the coloured lines have poor contrast. Please consider changing and add the colour information in the caption too.

AC: We thank the reviewer for this suggestion. Agreed. The authors have updated the caption to aide this comment. The authors have also changed the colours to orange and blue for better contrast.



"Figure 8. Variability in DEDs in 2018 and selected seasonal variables that affect dust emission. The vertical bars display the total number of dust event days recorded by AERONET from AOD_D per week. The AERONET station was recording from 14/05/18 until 21/10/18, but no data was recorded between 24/07/18 - 14/08/18. Average weekly snow depth (cm) displayed with the solid black line and average weekly air temperature (°C) displayed with the orange dot-dash line recorded at the Lhù'ààn Mân Research Site. Lake height displayed with the blue long dash line is taken from the Environment Canada lake depth gauge 09CA001 at Kluane Lake near Burwash Landing and is the average weekly water depth at that site."

RC1: Line 455-459. Please note that while relaxing the threshold criteria makes sense, it also introduces the possibility of cirrus contamination in the Aeronet data. I think and only in this case, it can be circumvented by inspecting the remote camera images for the days with Aeronet observations and check if there are cirrus in the background sky. This could be a quick and dirty way to check that Aeronet data is not contaminated.

AC: The authors thank the reviewer for comments on cirrus contamination. An investigation of available RC images to note the occurrence of cirrus cloud is currently being conducted by co-authors. At the time of the study, only one day (24/05/2018) of RC data was available to be analysed. To help mitigate the effects of cloud, the authors have investigated MODIS Terra imagery and added information on cloudy data to the supplementary information (Table S1).

RC1: Line 457. This is the first instance that Figure 9 is mentioned and it is referred in way as the reader is already familiar with the figure, which is not the case. So please rearrange the text to first introduce the figure and the refer to different sections of it.

AC: We thank the reviewer for this suggestion. The authors agree and the ordering of the manuscript was adjusted so that figure 9 comes earlier.

RC1: Lines 476-480 and 486-490. While I think it makes sense to use thresholds used in other Aeroent dust sites for this case, it is not entirely surprising that there are detection differences. First of all , this site is extremely close to the dust source something that not necessarily is the case in the reference sites used in lower latitudes. In particular, the rapid variability of dust concentrations in puffs of dust is probably one of the main differences. So for example, given the distance to the source, it is likely that this dust has a higher coarse mode contribution to the observed AOD and AE than in lower latitude sites. While I do not think that you can do much to improve on this, I do think that this fact should be mentioned and discussed as probable impacts in observed AODs and AEs.

AC: The authors agree with this statement and thank the reviewer for raising the issue. We have updated the discussion to mention and discuss these topics. The manuscript now reads:

"Further exploration of other AERONET products, for example the Spectral Deconvolution Algorithm (SDA), may further help define thresholds for HLMA. Furthermore, it is also important to note the location of the AERONET station relative to the dust source. KLRS is extremely close to the dust course which contributes to rapid variability in dust concentrations which will not be seen at mid-latitude locations far from source. It is likely that dust from this site will consequently have a higher coarse mode fraction that the AOD and AE at mid-latitude sites." [Lines 520-523]

RC1: Line 503-504. Not clear what you mean with "aerosol phases" , what are you referring to?

AC: We thank the reviewer for this suggestion. This was also raised by reviewer 2 and we have changed the text to ‘aerosol types”. The manuscript now reads:

“SSA was derived for the aerosol types show that dust scatter the most incoming radiation with biomass burning aerosols scattering slightly less (Figure 11c).”

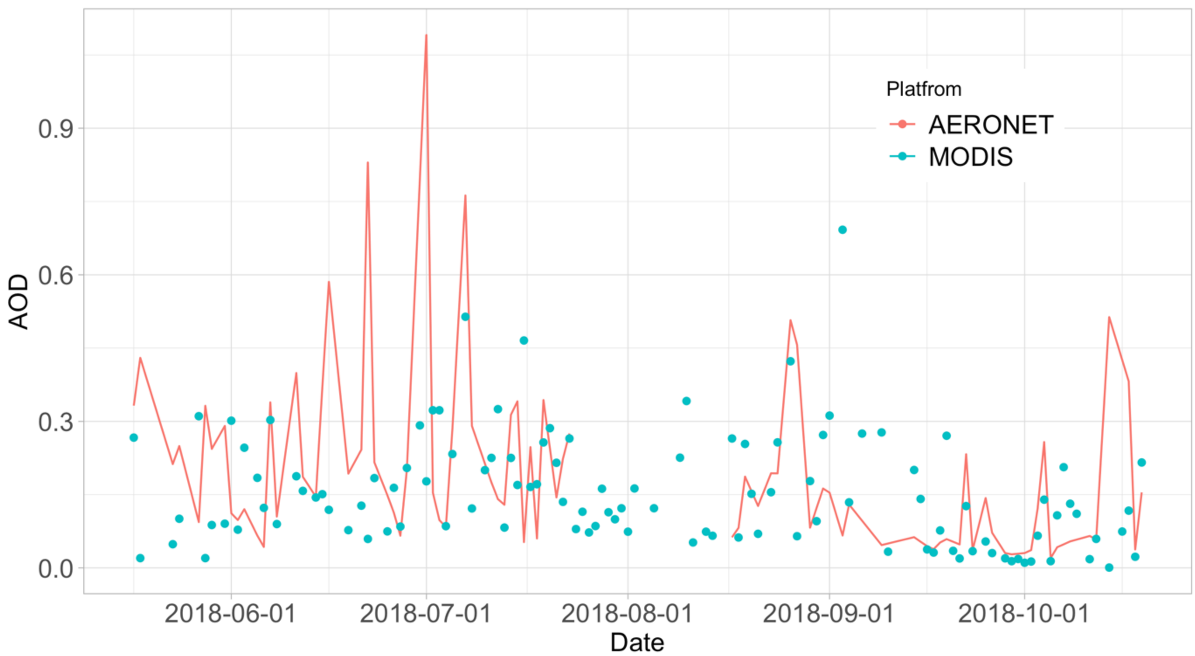
RC1: Figure 11 Caption: Add a clarification that Aeronet retrievals of size distribution and SSA are carried out only for AOD>0.4.

AC: The authors agree, and the manuscript was updated to clarify this point. The manuscript now reads:

“Models used to calculate volume size distribution are based on AERONET level 2.0 DQ with and AOD > 0.4.”

RC1: Figure 13: the way this is plotted, it suggests MODIS observed the area continuously which probably it did not happen. Can you add symbols to the days where there was a MODIS observation?

AC: We thank the reviewer for this suggestion. The authors have updated this figure to remove the continuous line of MAIAC data and have updated the figure with colours. Figure 13 has also been moved and can now be found in supplementary information figure S5.



RC1: General comment triggered by Figure 13

One reason why MODIS may have trouble in this place is that the MODIS pixels are too big, or the observed pixel contains variable combination of bright and dark surfaces all in one pixel that can't be accounted for the retrieval. So perhaps you could clarify somewhere the width of the valley. For example, MODIS pixels are in the 500-1000m size. How do these compare with the typical size of the dust sources in the flood plain?

AC: Thank you. We can clarify this point as follows: The valley floor is 4-5 km wide. The MAIAC pixel size used in this study were 1km by 1km. The dust plume size is often bigger than this (around ~25 km^2). The manuscript now reads:

" 1 km by 1 km pixels within the 70km^2 southern portion of Lhù'ààn Mân was analysed in this study. The mean MAIAC AOD retrieval for each day was then used for analysis. The valley is 4-5 km wide, and the dust plume size is often bigger than this (around ~25 km^2). With dust advecting over the lake a uniform brightness background should aid in MAIAC AOD retrieval." [Lines 315- 319]

RC1: Perhaps, it would be illustrative to add a MODIS/VIIRS RGB of one event to illustrate how poorly the plumes are resolved (it will lucky very fuzzy). Just suggestion, it maybe informative for a presentation but probably take too much space in the manuscript.

AC: We thank the reviewer for this suggestion. The authors agree and have added an image of a MODIS captured dust plume into the supplementary information (Figure S4).

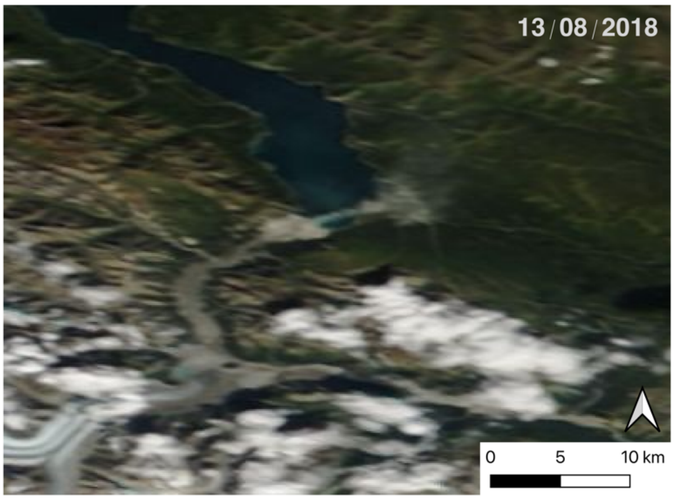


Figure S4: MODIS Terra Image of a dust plume blowing over KLRS on a clear day. Plume length (from end of delta to end of plume) is ~ 8km.

RC1: Line 579 ... detected by?

AC: The authors agree with this and the manuscript now reads:

"At Lhù'ààn Mân, an exceptional frequent emitter of dust, more than 97.8% of events are not being detected due to AERNET cloud screening algorithms."