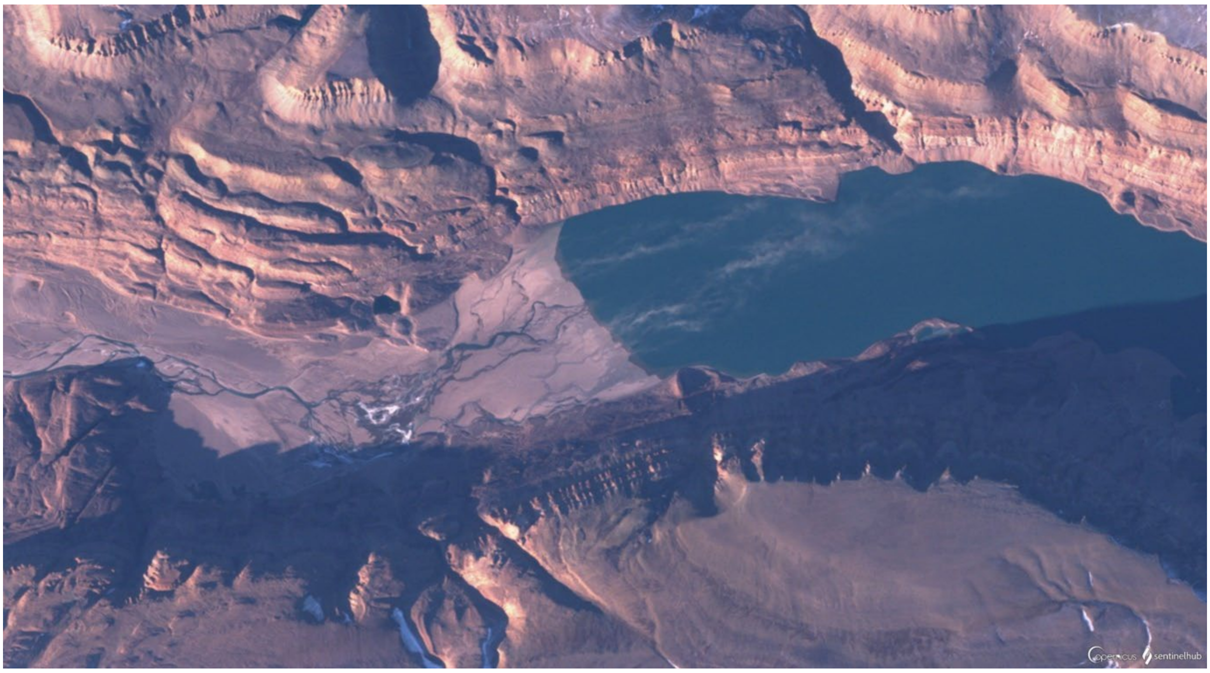

Project completion report for ESA-Future Earth Joint Program:

“Constraining High Latitude Dust activity in Greenland using the Sentinel constellation” (ESA-2022-02)

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Introduction

After a competitive application process made open to all second and third year Loughborough University undergraduate students who had completed any of the Geographical Information Systems (GIS) and remote sensing modules at Loughborough, there was a total of 11 skilled student applicants. Two undergraduates of excellent calibre at different stages of their BSc Geography degrees were selected for the two intern analyst roles available on the project; Alexander Hall (at the time, in the summer between his second and final year) and Joseph Rideout (in the summer following his graduation). Per the original proposal, the funding from ESA-FE was used to pay wages for each student for 8 weeks of their time, to receive training and then deliver work on the project objectives. Starting mid-July in 2022, Alex and Joe carried out the vast majority of the work in-person, based over summer in the Loughborough Geography Geospatial Lab (Figure 1).

Figure 1: Student workers Alex Hall (centre) and Joe Rideout (right) hard at work in the GIS lab, August 2022.

After a first week of training on Sentinel-2 and -3 data acquisition and discussion of research design and steering input from the SOLAS team member, weekly meetings were subsequently held between the UK team members to discuss progress and preliminary findings, adapt the workplan as required and troubleshoot problems.

From the original proposal, there were two planned aims for the project;

A1) determine, at high resolution, the locations of active dust emission for a four-year period (2018-2021) for Alaska and Greenland,

A2) assess the potential for quantifying mineral dust atmospheric loads in the regions immediately downwind of identified source areas, for a series of case study dust events.

These were to be delivered via two specific Work Packages:

WP1: Use Sentinel-2 data to establish a spatial and temporal inventory of observed dust point sources for Greenland and Alaska. Inventories will be used to determine emissive types of land surface, and survey instances of repeat or unique emission. (Wider field-of-view, coarser scale monitoring of multiple, active source areas in regional dust events will come from Sentinel-3.)

WP2: Use Sentinel-5P aerosol index to quantify the relative magnitude of mineral dust burden detected during dust events. This package will also investigate the influence of environmental drivers on observed dust loads from specific sources (e.g. particular valleys) for different dust events, as related to variables such as near-surface reanalysis windspeed data.

As the project unfolded, it became clear that the emerging success but associated time commitment associated with Aim/Work Package 1 meant it would be preferable to concentrate on WP1. It was decided at the halfway point that the project should focus solely on delivery of WP1, but to increase the period of study (extending the annual range of imagery analysis (2016-2021), with Aim 2/WP2 to be saved for future work.

Methods

WP1 Alaska: For WP1, and for building the student interns' experience in the interpretation of dust in true colour imagery, the study began in Alaska due to this being the best understood regional dust system between it and Greenland. The wide viewing swath width of Sentinel-3 allowed for efficient viewing of daily imagery covering the whole of the Gulf of Alaska study area. Despite a range of spectral enhancements for dust detection being published for sensors such as MODIS, these enhancements have been traditionally optimised for dust in suspension over warm, bright, desert land surfaces. Where dust plumes occur over dark water such as the Gulf of Alaska, their contrast makes them readily identifiable, improving the effectiveness of simple true colour imagery for dust detection.

In this study, true colour imagery from the moderate resolution OLCI sensor on board the Sentinel-3A/B platforms was inspected daily over the Gulf of Alaska between 136°W and 164°W for a 6-year period (2017-2022). OLCI on Sentinel-3A/B has a daily overpass with a large swath with visible wavelength bands at 300 m spatial resolution. For each day in the study period, the study region was inspected for the presence of dust plumes in true colour imagery (Figure 2). To help determine the presence of dust when necessary, the distribution of Dark Target AOD and Angstrom exponent values were consulted from MODIS Terra (with its comparable pre-local noon overpass time to OLCI) via the NASA Worldview data platform. Where dust was visible over the ocean, the source was determined by inspection at the upwind edge of the dust plume when traced back over land and a database of point sources was built. This systematic imagery analysis provided both the dates of dust events and their origins so that a record of the temporal and spatial variability of dust from high latitude sources neighbouring the Gulf of Alaska was developed.

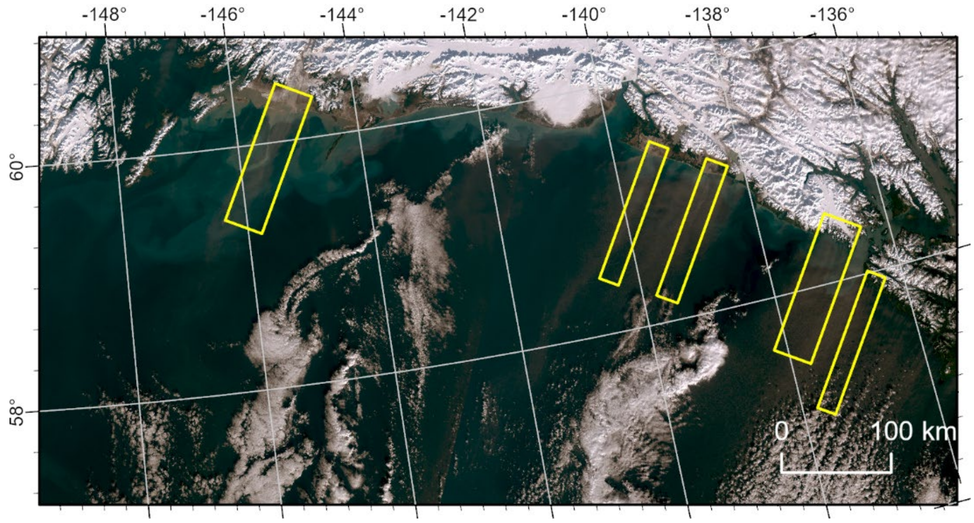

Figure 2: Example Sentinel-3 OLCI true-colour image from November 6th 2022 showing multiple dust plumes heading into the Gulf of Alaska.

As the dust activity/source location inventory was built, an important consideration soon emerged in terms of the frequency that imagery from Sentinel-3 was useable for the purposes of dust observation. In particular, cloud and polar night meant the availability of useable images was variable, meaning that any meaningful interpretation of the dust activity record from the satellite would have to be alongside an assessment of cloud-free data availability. To quantify the potential for dust observation based on cloud-free days, for the dominant dust source that borders the Gulf of Alaska (the delta/mouth of the Copper River), each day for the study period was inspected to produce a record of imagery condition and one of the following specific categories was ascribed; cloud-impacted, clear but dust free, clear with dust, polar night, or missing data.

WP1 Greenland: When WP1 switched attention to Greenland, the spatial resolution of Sentinel-3 used regionally for Gulf of Alaska was found to be inadequate for visual monitoring of dust sources and source determination. The often small areal extent of topographically-constrained (valley) sources meant Sentinel-2 was a much more effective instrument to pinpoint sources.

While the distribution of dust sources in Greenland is poorly understood, from the literature it is known that where fine sediment gets stored in the landscape, for example in valleys with active glacio-fluvial processes, as well as geomorphological features like alluvial fans, such places represent candidate dust sources in the high latitudes. The major (and highly novel) effort of this project went into a systematic Sentinel-2 led inspection of candidate sources over all of Greenland.

From Sentinel-2 imagery, all candidate dust sources were identified over Greenland (over 1100 source sites). For each candidate source an efficient workflow to review the imagery inventory for dust occurrence was to focus spatially on a given candidate location and then build a timelapse of imagery. This executed via the Sentinel-Hub EO Browser* imagery viewing portal. Timelapses were populated under the rules of one image per day, for scenes with >50% of Sentinel tile coverage, but <65% cloud cover. Depending on latitude (with frequency of source-imagery effectively increasing at higher latitudes due to overlapping orbits), this produced between around 300-600 sampled images for each candidate source over the 2016-21 sampling period. Each timelapse image-series was than manually scrolled through to determine any day with dust. Overall, this method led to the (gruelling!) inspection of around 400,000 Sentinel-2 images to identify locations of observed and non-detected dust activity (Figure 3).

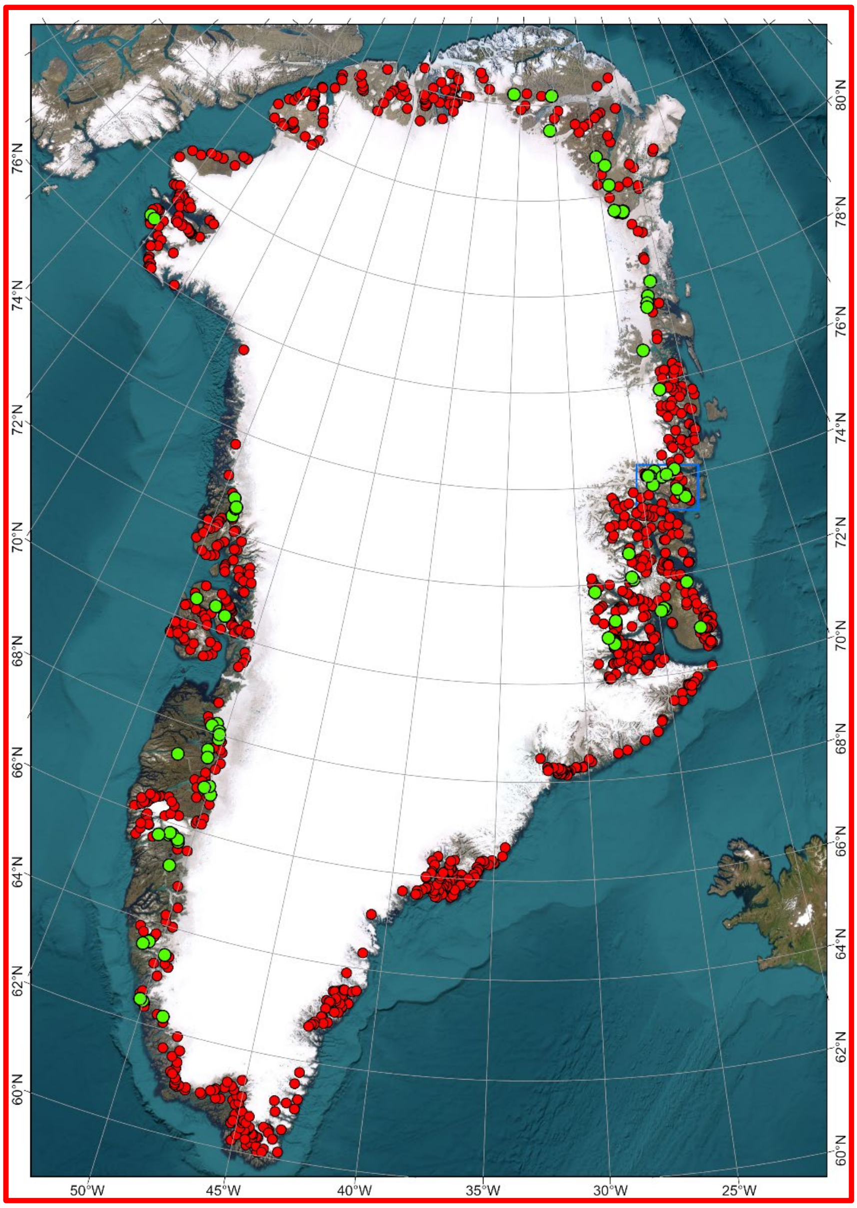

Figure 3: Candidate sources seen to produce dust (green dots) and all non-detection sites (red dots) systematically examined over Greenland with Sentinel-2 imagery, 2016-21.

This approach was labour intensive and is fundamentally based on user subjectivity/interpretation, but the two student analysts working in tandem and with constant quality control by supervisors, plus the experience that develops after familiarity with study makes this a successful method with confidence in careful results. The visual inspection of true-colour images to determine point sources of dust plumes remains a recognised method in the literature to derive such databases.

**The functions of the Sentinel-Hub data portal are also replicated by tools in the Copernicus Data Ecosystem visualizers for Sentinel-2.*

Findings

WP1 Alaska: While the Copper River is a recognised dust source in the Gulf of Alaska region, this study's results of dust observations a) indicate for the first time the frequency the Copper River delta behaves as a dust source based on systematic multi-year monitoring, and b) the relative activity of similar glacially-connected fluvial systems bordering the gulf, thus identifying all the major (regional) sources of mineral dust input into this marine system (Figure 4). With the Copper River location associated with 46 recorded dust detections over the six years, 7.7 events per year is comparable to moderately active low latitude desert dust sources, though direct comparisons are difficult to make. Between 138 and 140°W, the deltas of the meltwater-fed Alsek and Dangerous Rivers emerge as additional prominent dust sources, with about half the dust event frequency of the Copper River.

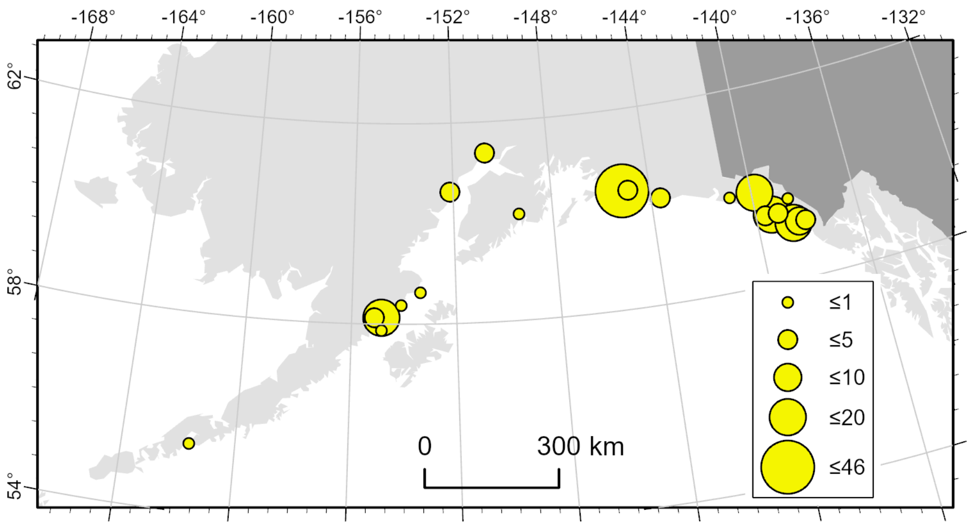

Figure 4: Total frequency of dust source activity (observed days with dust events) proximal to the Gulf of Alaska for 2017-22, based on Sentinel-3 image inspection.

For the Copper River, September, October and November dominate the 5-year observation record (Figure 5) with dust events occurring on average for 19% of November days, which helps to quantify the seasonality of dust frequency and prevalence of dust in autumn. Figure 5 however also reveals that on average 91% of days in July for an area of interest fixed over the Copper River delta were cloudy, with implications for possible missed dust events and biases in assessing dust activity from remote sensing (including from data products like Aerosol Optical Depth which are also impacted by cloud).

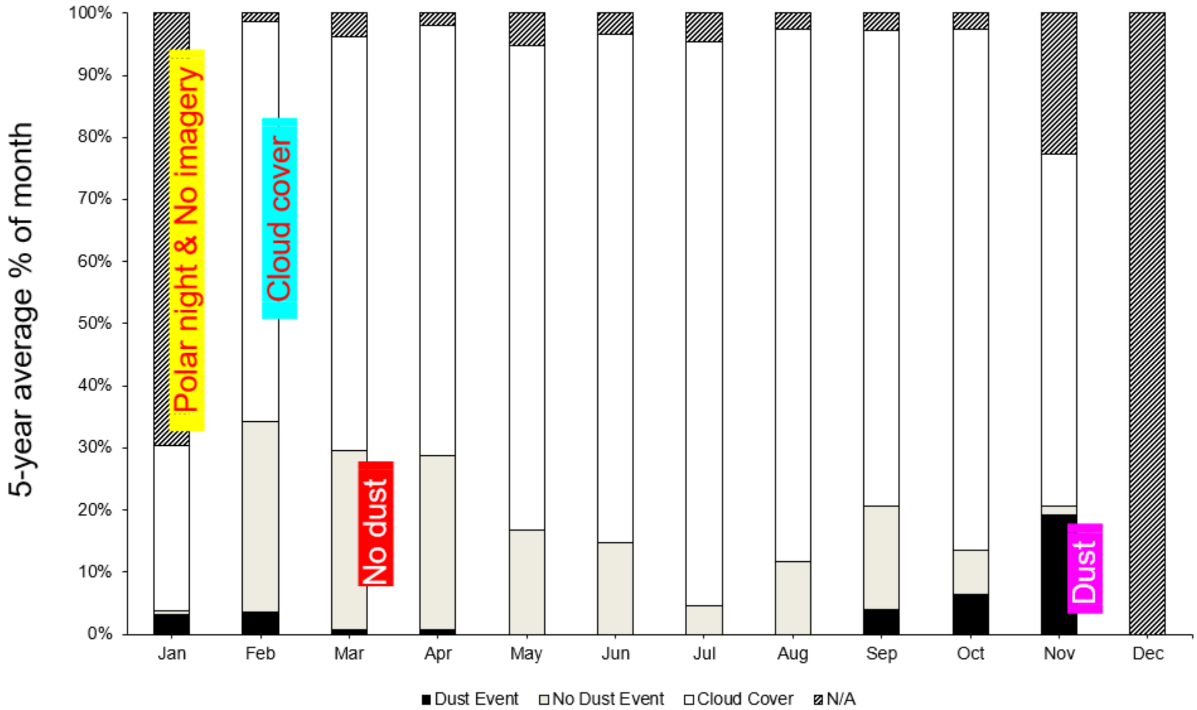

Figure 5: Average proportion of each month categorised by nature of Sentinel-3 scene for 2017-21. "N/A" category represents Polar Night or No Overpass coverage.

WP2 Greenland: Of the >1100 candidate dust sources examined, the systematic inspection of Sentinel-2 revealed 83 sources that were observed to have actively emitted dust at least once in 2016-21 (Figure 6; with example dust event plumes for one source shown in Figure 11). For the study period, there were 243 occurrences of dust activity detection across all observed sources, with the most active observed source emitting dust on 25 different (unique) days. Around half (53%) of the active sources were only observed to be emitting dust on one day in the study period, while 13 (15%) had 6 or more, i.e. on average, at least one detected blowing dust event per year. Across all sources there were 140 individual days with at least one source active, occurring through the year between April and November, but with just over half of all events detected in September and October.

In terms of imagery retrieval, for sources identified at ~82ºN (numbered source 22), five months are fully polar night, but high overlap of viewing due to orbit crossover at this latitude means 'no imagery' was relatively rare. Cloud varies between 30-60% (Figure 7). At a monitored source at ~67ºN (Source 28), days missed between repeat imaging due to overpass day was around 45% of non-night months, but cloud obfuscation of the dust source was maximally c. 30%.

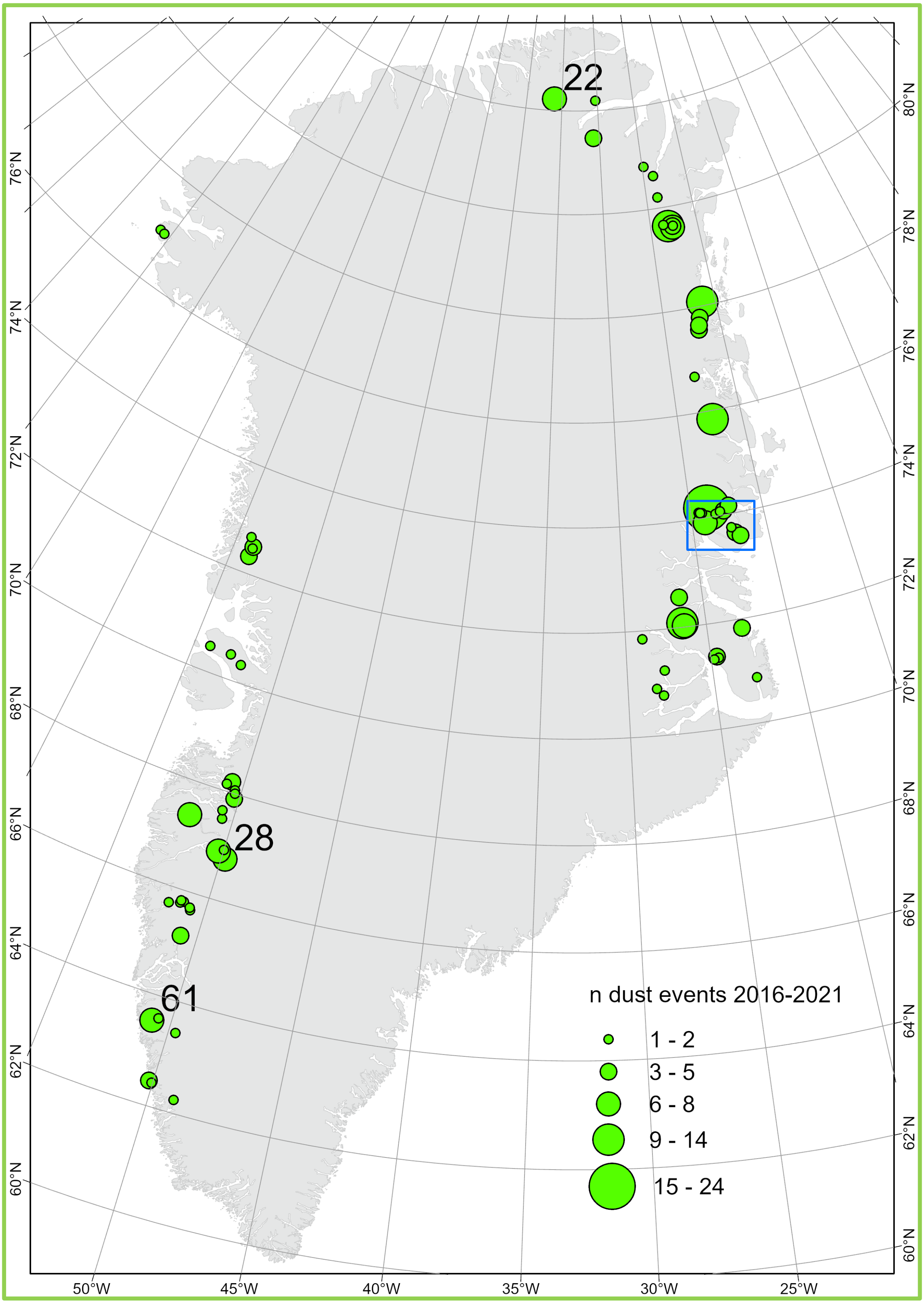

Figure 6: Frequency of dust observation per active source identified in Figure 3. Bold numbers indicate sites of imagery sampling rate assessment (Figure 7).

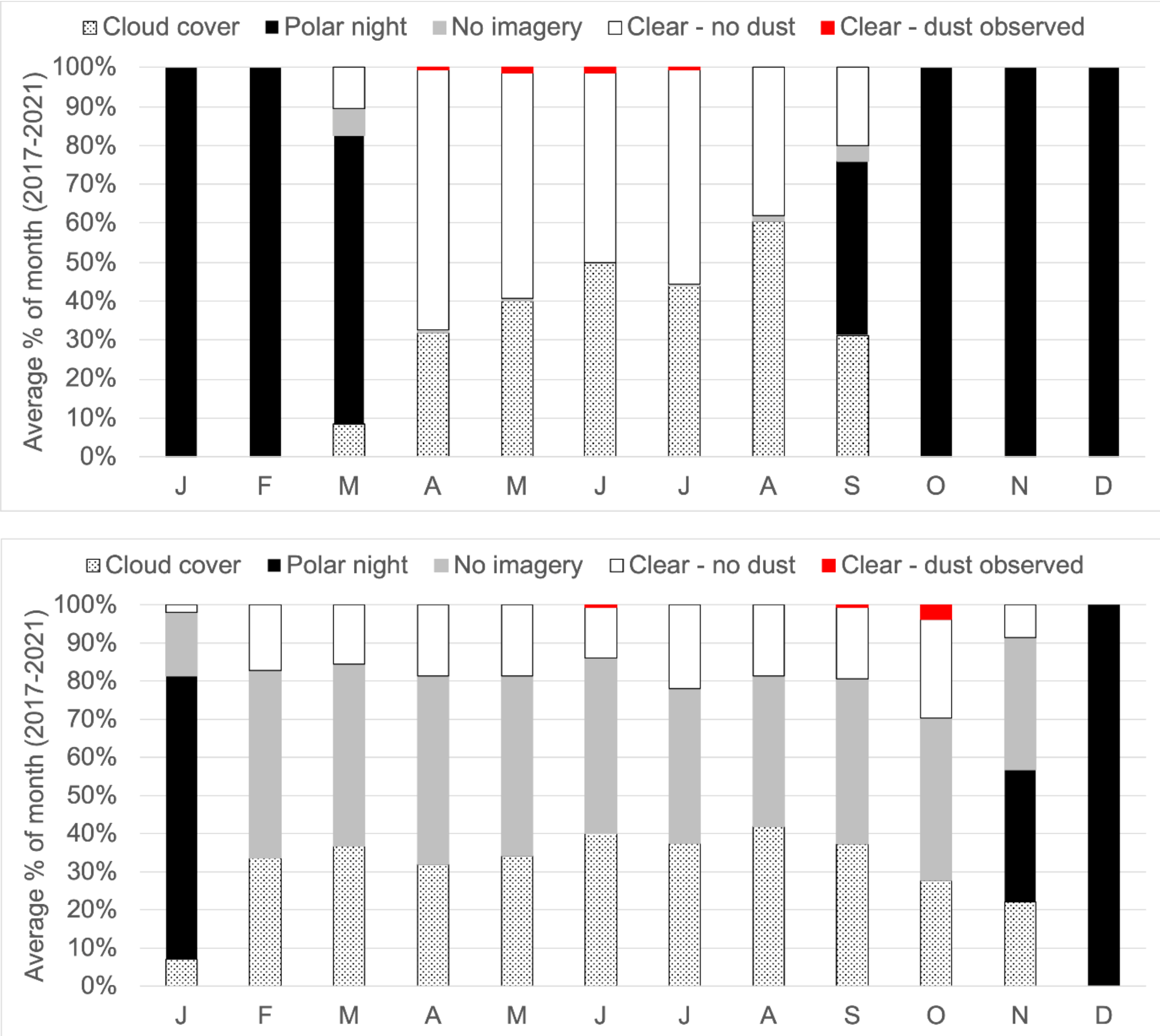

Figure 7: Average availability of Sentinel-2 imagery at different latitudes, from (top panel) Source 22 (>82ºN), and (bottom panel) Source 28 (67ºN).

Figure 7 shows how from the systematic assessment of Sentinel-2 retrievals, biases in sampling make it difficult to determine relative seasonality of source activity, but, for example, it is worth considering that wintertime polar night will also be associated with more frequent snow cover. This means reduced propensity for emission (due to snow cover on the ground) occurs when visible-band retrievals are absent due to lack of solar illumination.

Final Workshop: The wrap-up workshop was held online on Friday April 21st 2023. While the UK members of the project team had maintained weekly contact with the work, the wrap-up also saw the final presentation to the SOLAS element of the work through the SOLAS steering member of the team, Santiago Gassó, alongside invited external European high latitude researchers; Christian Junger Jorgensen (Aarhus University, Denmark) and Throstur Thorsetinsson (University of Iceland). Thomas Gill (University of Texas-El Paso) a desert dust specialist could not attend on the day due to health reasons. Sophie Hebden and Bridget Blake were representing Future Earth.

The workshop was very fruitful and one novel output that has stemmed from the discussions it prompted has been a follow-up attempt to classify all active Greenlandic sources from WP1 based on their underlying geomorphology/landform (Figures 8,9). This value-adding research effort to identify the types of land surface associated with blowing dust was facilitated by the high spatial (10 m) resolution of Sentinel-2 MSI which provides the necessary detail to interpret landscapes. Knowledge concerning the relative dust emissivity of different land surface types can inform future attempts to model dust emission by helping tune dust simulations to ensure they represent surfaces' different propensity to emit dust. This information will go on to open up conversations with dust modelling specialists for collaboration.

Figure 8: Preliminary classification of active source geomorphology, grouped broadly into 'Delta', 'Glacio-lacustrine' and 'Other' classes, then by distinct sub-types. Interestingly for considering how dust emission from Greenland will change, theses different geomorphologies have different potential for changing dust emissivity in response to sea level change, glacial retreat and increased meltwater regime.

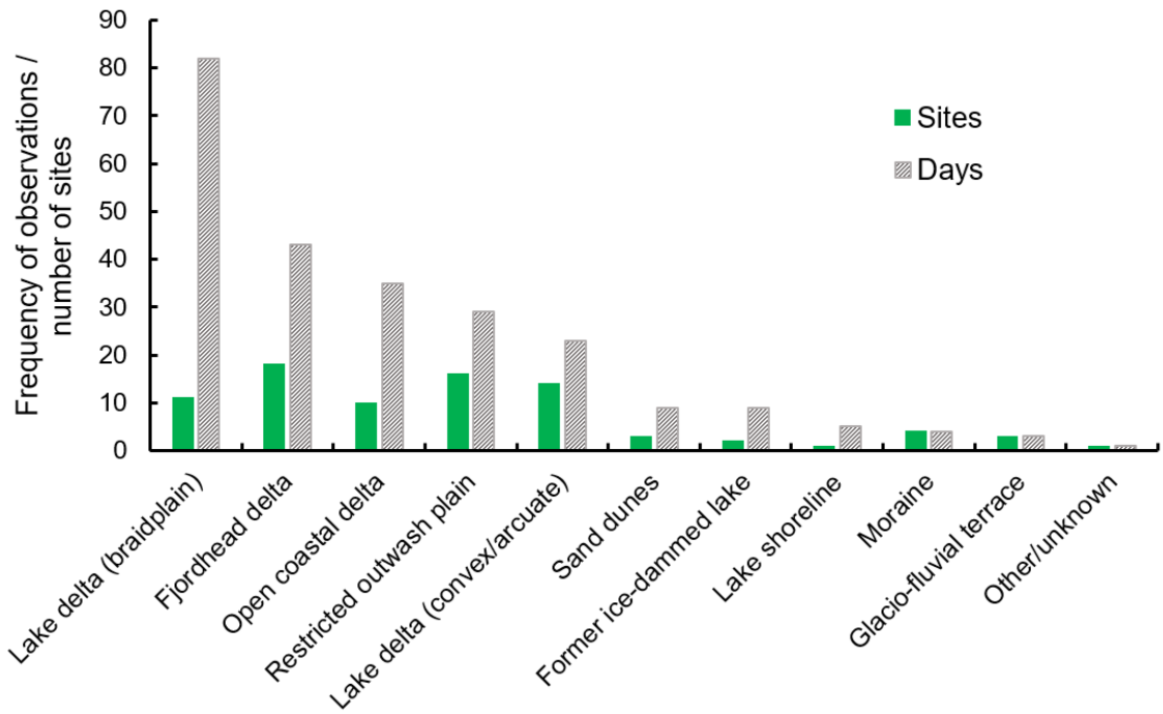

Figure 9: Frequency of Greenland dust observations (total days with dust detected) 2016-21 for all sources associated with different geomorphologies classified in Figure 8.

Also during the workshop, after seeing the form of dust observation record that could be derived over the natural sources that were inspected in the project using Sentinel-2, a notable idea from external contributor Christian Junger Jorgensen was to conduct a similar systematic monitoring campaign over possible sources of directly anthropogenically-associated dust in Greenland. Of particular interest would be examining dust outbreaks associated with new mineral mining developments which have begun inside the Sentinel-2 era.

After the formal completion of the workshop, considerably more work has continued which drives the research forward. In the subsequent summer of 2023, some additional wage money was used to fund Alex Hall (in his summer post-graduation) to further develop WP1 for Greenland Sentinel-2 to include the additional year of 2022. Thus the Sentinel-2 source database for all of Greenland and publication will now cover 2016-2022.

Outputs

Presentations

To date, the results of the project have been disseminated widely including by multiple oral and poster presentations at a range of international science meetings, including aeolian specialist and high-latitude environments/remote sensing joint themed:

Baddock, M., Hall, A., Rideout, J., Bryant, R., Gassó, S. and Bullard J (2023) *Constraining dust sources in Greenland with Sentinel-2.* Poster presentation at the 11th International Conference on Aeolian Research. Las Cruces, New Mexico, USA. July 2023.

Bullard, J. Baddock, M., Hall, A., Rideout, J., Bryant, R. and Gassó, S. (2023) *Location, timing and trajectory of dust emissions from ice-free Greenland.* Oral presentation at 2023 UK Arctic Science Meeting. Cambridge, UK. September 2023.

Bullard, J. Baddock, M., Hall, A., Rideout, J., Bryant, R. and Gassó, S. (2023) *Location, timing and trajectory of dust emissions from ice-free Greenland.* Oral presentation at the ESA Fluvial-Aeolian Interactions on Planetary Surfaces (FAIRPLAY) conference and workshop. Noordwijk, Netherlands. November 2023.

Bullard, J. Baddock, M., Hall, A., Rideout, J., Bryant, R. and Gassó, S. (2024) *Location, timing and trajectory of dust emissions from ice-free Greenland (2016-21).* Oral and poster blended presentation at Arctic Observing Summit (AOS) Conference. Edinburgh, UK. March 2024.

Journal papers in preparation

The core findings from Alaska and Greenland are currently being written up separately for papers with intended submission in 2024. (Criteria of success for the project proposal stated two publications, and while these are not yet completed, the body of work completed during the funding will certainly sustain the predicted papers.)

Baddock, M., Hall, A., Rideout, J., Bryant, R., Bullard, J. and Gassó, S. (in preparation for *Weather*)

Baddock, M., Hall, A., Rideout, J., Bryant, R., Bullard, J. and Gassó, S. (in preparation for *Geophysical Research Letters*) *High latitude dust sources proximal to the Gulf of Alaska.*

Bullard, J., Baddock, M., Hall, A., Rideout, J., Bryant, R. and Gassó, S. (in preparation for *Science Advances*) *Cryospherically-linked dust emissions from ice-free Greenland.*

Research Capacity Legacy

- The new dataset provided by the satellite analysis of the Future Earth-ESA project has underpinned the involvement of Bullard and Baddock in a £3.6 m bid to the UK's Natural Environmental Research Council (NERC) national funding body. Unfortunately, in March 2024 the funding application result was announced as close, but unsuccessful.
- In November 2023 a funding application to the UK Royal Geographical Society's Walters Kundert Award (for research in high latitudes or high altitudes) was submitted to support a follow-on project. This new proposal

intended to set up detailed ground monitoring of one of the WP1 identified Greenlandic dust sources to better quantify the extent of dust activity missed by the low earth orbit satellites/sensors (such as Sentinel-2&3, Landsat 8&9, MODIS, PlanetScope) due to overpass times, cloud cover etc. While highly praised for its originality, again, in March 2024 this funding application was unsuccessful. The RGS application involved Christian Junger Jorgensen, and this collaborative link was established due to the ESA-FE wrap-up workshop.

- On the back of the ESA-FE funded project, a competitive UK NERC-funded PhD scholarship was advertised at Loughborough University to develop the successful work further, including through climate reanalysis and ground-based observations in Greenland to better determine the rates that dust activity was missed by LEO satellites at high latitudes. On the back of the experience provided by the ESA-FE joint project, Joseph Rideout successfully won an offer for this studentship, but unfortunately could not ultimately take it up. In the second round of the PhD being offered, and with the studentship becoming co-developed with the other original intern, Alex Hall, Alex successfully won and has now accepted the studentship in March 2024. This excellent news means Alex will begin his PhD later this year in October 2024. (The science experience of the project helped Joe secure the job he currently holds environmental standards officer for a London metropolitan council.)

Follow-on Work

- Quantifying dust activity using aerosol optical depth using Sentinel-5 for dust events, the theme of the proposal's WP2, remains an area of interest for further research. Given a long time-series of known dust events was successfully produced for Alaska and Greenland in WP1 there is now a database for which the extent and magnitude of these events could be validated via Sentinel-5, pushing beyond the simple derivations of frequency and user subjectivity initially produced here.
- With Alex's commitment to a PhD, there are fruitful possibilities for a close examination of the meteorological drivers associated with satellite-observed dust activity. Developments like the high temporal and spatial resolution climate reanalysis of CARRA (Copernicus Arctic Regional Reanalysis, available on a 2.5 km grid and at 3-hourly timesteps) will allow dust-driving variables to be derived for the times of satellite-observed dust events. The 'artificially' frequent overpass due to overlapping orbits at the high latitudes highly increases the cadence of source monitoring which can be taken advantage of. For the period of 17-25th April 2020 for example, 32 Sentinel-2A/B overpasses occurred over a dust source at 82°N, and the associated windspeed and direction record from CARRA is shown in Figure 10 with a selection of associated imagery in Figure 11.

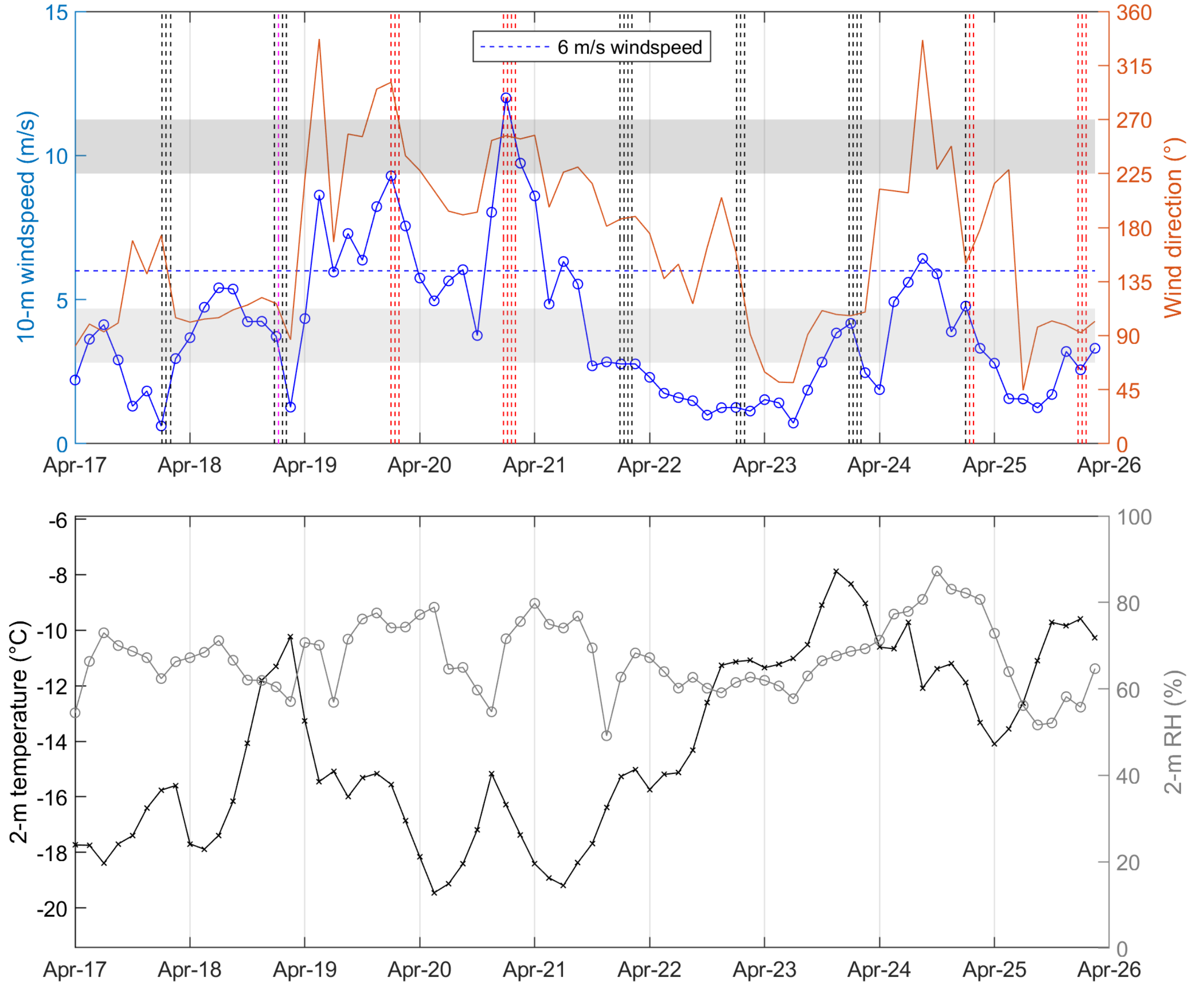

Figure 10: Top) Time series of 3-hourly CARRA reanalysis windspeed and wind direction at 10 m, and B) 2-m air temperature and relative humidity for Source 22 (As marked on Figure 6) through the period 17-25th April 2020. The dashed horizontal line in the top panel shows a 6 m/s indicative threshold for aeolian activity. Dashed vertical lines in top panel indicate all overpass times of Sentinel-2A/B, where black indicates overpass with no dust plume visible (19), red indicates dust plume visible (12) and magenta indicates a cloud-blocked scene (1). The dark grey horizontal patch highlights down-valley wind directions from SW-W, and lighter grey patch marks up-valley winds from ENE-ESE.

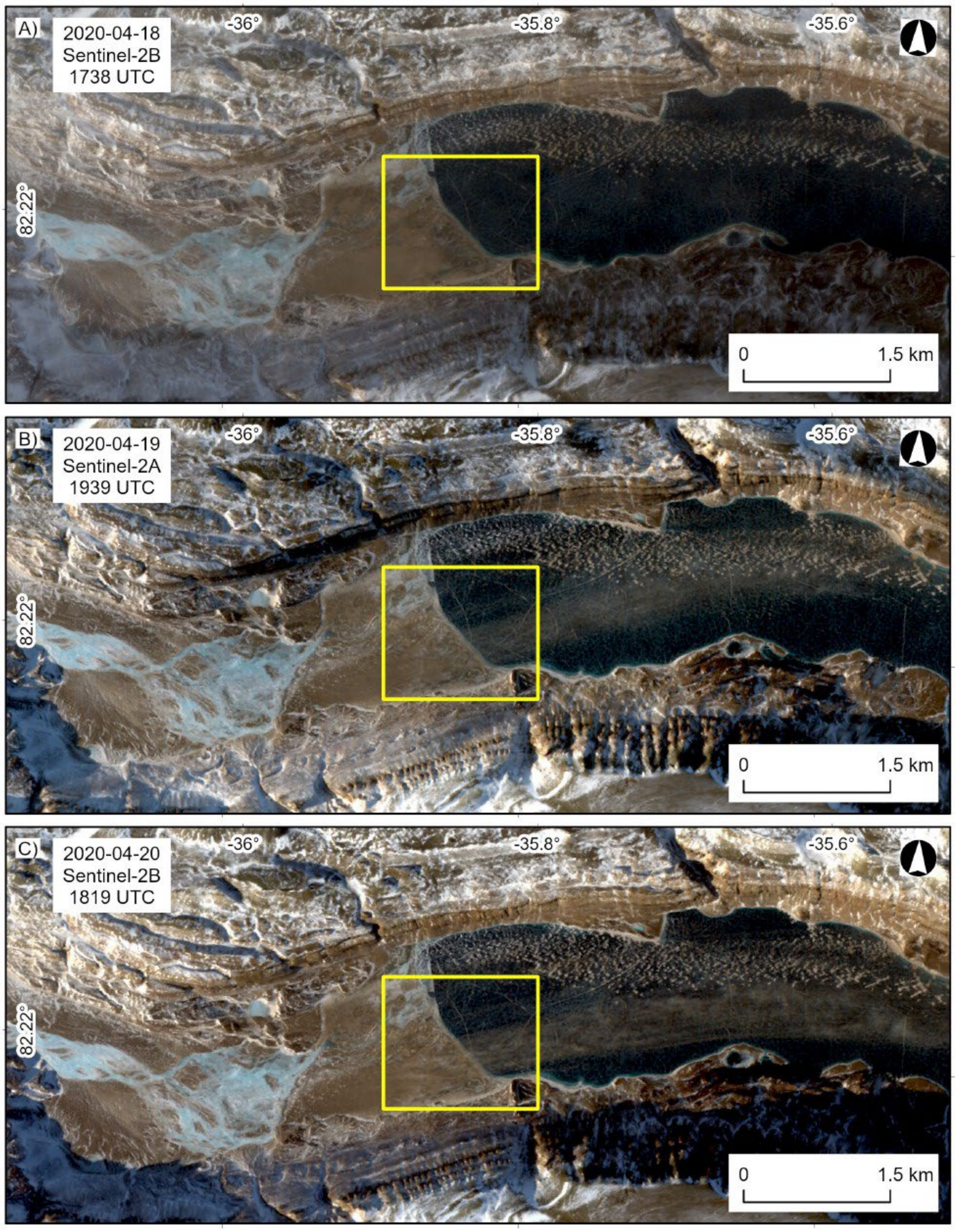

Figure 11: Sentinel-2 true-colour images over Source 22 (as marked in Figure 6) for selected days from the focused study period in late April 2020. A) Dust-free scene on April 18th, B) down-valley dust event captured on April 19th, C) well developed dust plume extending over the source-bordering Midsommer Sø lake water body to the east, April 20th. The common yellow box highlights the land surface region with the upwind points of visible plumes for comparison with the dust-free state.

Summary

While labour-intensive and generally technically simplistic in terms of the remote sensing data used (relying on true-colour imagery), the findings and the dust source datasets generated by this study are sincerely novel, and provide an excellent first-order understanding of the spatial variability of dust in two regions with global significance as high latitude dust source regions; Gulf of Alaska and Greenland. The work has taken a critical evaluation by also carefully determining the extent to which Sentinel-3 and Sentinel-2A/B retrievals do offer useable imagery to study activity of dust sources at these latitudes. Any assessment of the temporal variability of dust occurrence frequency needs to be underpinned by knowledge of biases in sampling by any given sensor, due to technical (orbit, swath width) or environmental (cloud variability, polar night) factors/constraints.

The user-led approach and the findings reported here are exceptionally useful. Efforts to automate dust detection using machine learning, drawing on cloud-based stores of imagery are developing, but *systematically, user-derived inventories of dust sources and events*, especially for such an unknown but intricate dust-bearing environment as Greenland, provide vital baseline understanding. From these attempts to automate image processing can be evaluated.

Very positively, the continuation of this work has been assured with Alex Hall's upcoming PhD position. This is an exciting prospect, and a direct result of the ESA-FE Joint Program funding.

All project participants from Loughborough University, University of Sheffield and University of Maryland thank the funders for their support and for enabling this innovative research which has helped shape not only the science in the field of mineral aerosol dynamics, but also the career trajectories of two bright young environmental scientists.