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Satellite observations of Arctic blowing dust events >82°N

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Abstract

This study reports satellite evidence for the most northerly blown dust activity yet observed on Earth. A systematic inspection of high-resolution satellite imagery identified active dust events and their sources >82°N in Peary Land, Greenland. In the absence of any local weather measurements, for all observed dust activity a focus period in April 2020 with multiple dust plumes, reanalysis climate data found the majority of dust events to be associated with windspeeds exceeding a typical threshold value for blowing sand and dust uplift. Wind direction variability points to dust-raising by cold airflow down-valley winds, likely from nearby ice masses.

Keywords

arctic weather; dust storms; mineral aerosols; CARRA

Introduction

Blowing dust is a common meteorological phenomenon in particular regions of the world. Dust events constitute formal weather-types that are recordable within synoptic observations, and whilst primarily associated with desert low latitudes, dust activity has long been recognised at high latitudes (Bullard et al., 2016; Meinander et al., 2022). The frequent strong winds of these environments, sparse vegetation cover in cold temperatures and a plentiful supply of fine-sized sediment provide the necessary conditions for dust uplift by aeolian (wind-driven) processes. In high latitudes, dust activity is closely connected to current or former ice extent, established partly by where fine sediment accumulates and also how ice masses influence weather, for example, by generating katabatic winds (Bullard, 2013; Bullard et al., 2016). Dust activity has environmental and societal significance wherever it occurs (Okin et al., 2011; Middleton et al., 2017), and in the high latitudes its impacts include air quality in settlements (e.g. Reykjavik, Thorsteinsson et al., 2011), nutrient inputs to ecosystems (Anderson et al., 2017; Crusius, 2021) and a role in ice nucleation and cloud formation as an influence on radiative budgets (Sanchez-Marroquin et al., 2020; Shi et al., 2022; Barr et al., 2023). To understand the controls on blowing dust, a key requirement is knowledge of the source areas from which dust outbreaks occur. Whilst research in the low latitudes has successfully produced satellite-based inventories of dust source locations (e.g. Baddock et al., 2011; Vickery et al., 2013), evidence concerning the locations of dust activity at higher latitudes, including the Arctic, is much less developed. This deficiency is partly due to impediments on dust source monitoring at these latitudes, as associated with cloud cover, seasonal polar darkness and the high-angle limitations of satellite sensors (Bullard et al., 2016).

For high latitudes, another challenge is the lack of at-source weather data and general sparseness of observations throughout regions. Such data availability is compounded by the spatially constrained and remote location of areas likely to act as sources of dust (Huck et al., 2023; Meinander et al., 2022). In fact, micrometeorological measurements made directly at-source in dusty environments are rare even in low latitudes and are usually only achieved by dedicated campaigns (e.g. Wiggs et al., 2022). In place of widespread observations, the advent of climate reanalysis data has been of considerable value for reconstructing the winds that lead to blown dust, through the analysis of these time- and space-gridded datasets at dust source locations. The recent Copernicus Arctic Regional Reanalysis (CARRA) effort is one such dataset specially developed for the Arctic (Yang et al., 2020). In particular, the high spatial resolution of CARRA (2.5 km) provides an enhanced way to look at meteorological variables in topographically complex areas (Køltzow et al., 2022). This is especially appropriate for dust studies at high latitudes because the preferential source areas where dust outbreaks occur are often associated with valley topography, as demonstrated by recent studies (e.g. Crusius 2021; van Soest et al., 2022; Huck et al., 2023). The extent to which CARRA can be used to elucidate dust emissions alongside satellite imagery remains an area of interest and, away from the few instrumented locations, the spatial variation of where dust events occur, when and how often they blow, represent important questions. The extent to which sources of dust are distributed latitudinally is one aspect of this uncertainty. Ranjbar et al. (2021) recently reported a case study of a dust outbreak near Lake Hazen in Nunavut, Canada (latitude 81.67°N). To date, this has been the furthest north satellite-based observation of blowing dust. Based on a review of high-resolution satellite imagery, the current study reports new observations of dust phenomena occurring >82°N in Greenland, with insights into the wind conditions associated with this most northerly of dust activity.

Methods

To investigate dust occurrence in far-north Greenland, European Space Agency (ESA) Sentinel-2 true-colour satellite imagery was systematically examined between 2016-2022 over 23 glacio-fluvial valleys >82°N that represent individual potential dust sources in the Peary Land region. The >82°N sector focused on here was part of a larger survey of dust sources in Greenland, based on Sentinel-2 due to the ground detail its 10-m resolution visible bands provide. The selection of the 23 candidate sources for inspection in the region was based on a imagery-based survey of valley topography containing identifiable loose sediment, as informed by the characteristics of typical source areas that have been recognised elsewhere at high latitudes (summarised by Bullard et al. (2016)). Imagery from Sentinel-2 is only routinely available to about 82.5°N and the coverage of potential sources inspected in the latitudinal band 82-82.5°N is shown in Figure 1. Using facilities available in the freely available Copernicus Data Space Ecosystem (https://browser.dataspace.copernicus.eu/), criteria were set to sample one image per day from Sentinel-2A/B, and to include all scenes with <65% cloud but >50% coverage of Sentinel image tile. The resulting imagery catalogue generated over each candidate source (typically >600 images over the 7-year period) was then manually inspected for the appearance of dust plumes.

For the 23 candidate dust sources systematically examined above 82°N, dust was observed at two locations in the Wandel Dal valley, at 82.22°N (Source A) and 82.19°N (Source B) (Figure 1). For Source A there were 13 different dates of dust detection over the seven-year study, and at Source B only a single date showed dust. CARRA reanalysis data were then obtained for all dust-observed dates, as well as a multi-day period to examine the most active dust period at Source A. CARRA variables are available 3-hourly and were obtained for windspeed, wind direction (both 10-m height) and 2-m air temperature. The modelled CARRA windspeed product has previously been tested in the north-eastern European Arctic and performed well against observations demonstrating an improvement for the region over ERA5, for example in capturing winds of polar lows (Køltzow et al., 2022). Accurately representing wind fields in complex topography can be a challenge for reanalysis products and Køltzow et al. (2022) report that the largest departure of CARRA from observed windspeeds is seen for sites such as coastal fjords which have some similarity to the terrestrial Wandel Dal valley landscape.

<<Figure 1>>

A key meteorological control on dust activity is exceedance of a threshold windspeed required for dust uplift. Estimates of threshold values are scarce for high latitude environments, but saltation (the hopping behaviour of sand grains along the surface during their wind-blown transport) is a recognised driving process of dust emission, related to sandblasting of the surface which liberates dust (Shao et al., 1993). If dry sediment of a typical sand grain size is assumed, a 10-m windspeed of ~6 m s^{-1} is a realistic lower value for saltation and thereby dust uplift (Bagnold, 1941). Such a windspeed magnitude was specifically linked to dust suspension in the Kangerlussuaq valley, south-west Greenland (Dijkmans and Törnqvist, 1991).

Results

For the two sources observed in Wandel Dal, the dates of observed dust represent a rate of 1.9 events per year for Source A (82.22°N), and 0.14 per year for Source B (82.19°N) (Figure 1). At Source A, the systematic examination of imagery showed blowing dust on three different springtime days in the last third of April 2020 (19th, 20th and 25th), exemplified in Figure 2bcd. One benefit for monitoring sites at extremely high latitudes is the multiple overpasses occurring each day for any given location due to overlapping coverage of low-Earth orbit satellites like Sentinel-2A/B (overpass record in Figure 3a) (Baddock et al., 2021). On 19th April, dust was seen blowing in all three overpasses that day, over the period 1759-1939 (all times UTC). Likewise, for the four overpasses on 20th April, all imagery showed observable dust, and again from 1728-1819 on 25th April. For a focused period of 17-25th April, a look at all available Sentinel-2 imagery (i.e. all overpasses each day and including those scenes with >65% cloud, originally excluded in the initial review) identified a further date with dust apparent (24th April, at 1849 and 1938). The high frequency of satellite overpass through this April period provided a clear record of occasional but repeated blowing dust. This cluster of events was also examined for the relationship between CARRA wind variability and satellite-observed dust for April 17-25th.

<<Figure 2>>

Linking the reanalysis data to the times when blowing dust was seen (and conversely, satellite overpasses *without* dust), the CARRA windspeed record helps account for three of the observed dust outbreaks (Figure 3a). The dust observations on 19th and 20th April both coincided with mean windspeeds (spatially averaged over the source) that well exceeded the indicative threshold of 6 m s^{-1}, reaching 7.9 (with a 8.5 m s^{-1} local maximum) and 9.1. m s^{-1} (9.2 m s^{-1} local maximum)respectively at 1800, nearest to overpass times. For the other two dates of observed dust, while the source-averaged windspeeds at 1800 were sub-threshold on the 24th and 25th, at 5.2 and 4.7 m s^{-1}, the local maximum speed over the source at 1800 on each day was 6.5 and 5.3 m s^{-1}. These maxima indicate that at the 2.5 km resolution of the CARRA grid, winds were above threshold over at least part of the Source A area on the 24th, and the plume observed at lower windspeeds on 25th is indeed smaller than the previous days' dust outbreaks (Figure 2d).

<<Figure 3>>

The wider relationship between blowing dust and the 6 m s^{-1} threshold can also be summarised across all dates when dust was observed from Sources A and B, as examined for 2016-22. For the 14 observed dust dates, the multiple Sentinel-2 overpasses that occur per day as exemplified in Figure 3, meant that based on the overpass timing, CARRA windspeeds from 23 individual 3-hourly times (either from 1800 or 2100 UTC) could be examined. For these 23 instances, the mean windspeed spatially averaged over the source nearest in time to a Sentinel-2 dust observation was 6.6 m s^{-1}, while the mean maximum windspeed over source was 7.3 m s^{-1}. In terms of spatially averaged windspeeds, 65% of the dust-linked times were greater than 6 m s^{-1}, while the local maximum windspeed was seen to exceed the assumed threshold for 70% of dust events.

Wind direction from CARRA matches the observed dust plume directions well for all outbreaks. Figure 3 indicates that three of the four observed dust events were down-valley (broadly westerly) winds, with dust plumes extending over the bordering lake body (Midsommersø) east of the source. The most developed plume was that seen at 1819 20th April where dust had extended >5 km over the lake (Figure 2c), corresponding well with reanalysis wind direction of 250° at 1800. On 25th April winds from ~105° agreed with plumes imaged as heading up-valley (Figure 2d).

Discussion

Different methodologies of determining dust event frequency make comparisons between places (and studies) difficult, but 1.9 events per year at Source A is comparable with frequencies of dust-coded daily weather observations found at some low-latitude desert margins (Engelstaedter et al., 2003). Despite such frequency being considered "per year", the window for likely dust activity from these high latitude sources is not a fully annual period, and there is reduced (or even zero) potential for dust activity through much of the year. Other studies have for instance shown that most high-latitude sources preferentially experience dust in the spring (e.g. later April, Figure 3), after winter snow cover has melted, but before valleys undergo inundation by summer meltwater flooding (Bullard et al., 2016). This pattern has been shown in southwest Greenland from dust-associated weather codes reported at Kangerlussuaq airport (67°N) (Bullard and Mockford, 2018). Snow-free valley surfaces before extensive meltwater inundation are evident in Figure 2, indicating the susceptibility of these springtime surfaces to yield dust when winds exceed threshold. Autumn periods, after summer melt has ceased and before the arrival of snow, also establish similar conditions (e.g. in Copper River of Alaska (Crusius et al., 2011)) and two of the 13 Source A events were observed in September. Furthermore, because the number of days when any given source can be effectively monitored for dust by satellites such as Sentinel-2 is variable – as controlled by satellite orbit paths, times of overpass/dust, polar night (~6 months of the year at 82°N, from mid-September to late March), and the variable presence of cloud obscuring the surface - the Sentinel-based annual frequency represents an unknown but undoubted underestimation of dust frequency at these >82°N sources. Regardless of the uncertainty surrounding the true frequency of blowing dust and the ability of satellites to accurately determine this (Bullard et al., 2016), our satellite analysis provides clear evidence of newly recognised dust activity at such latitudes.

This study also demonstrates how satellite observations establish known times of raised dust that can help determine wind's role in causing dust events. For example, the occurrence of three of the four captured events being associated with reanalysis winds >6 m s^{-1} in Figure 3a, and mean or maximum winds exceeding threshold for 65% or 70% of all dust observation times respectively, provides some confidence for predicting dust over the period considered here. As winds will be spatially variable inside topographic valleys it is not surprising that use of the maximum wind finds better agreement with the evidence of active dust blowing.

The onset of the first period of dust activity over the 19-20th April saw mean windspeed increase from 2.0 m s^{-1} at 2100 on 18th April to 11.1 m s^{-1} six hours later, associated with an abrupt switch from easterly to down-valley north-westerly flow (Figure 3a). This rapid wind acceleration with direction change occurred with a temperature drop of 6°C over the same period (Figure 3b), indicating the fast airflow was likely associated with cold air draining down the valleys leading from the ice mass <20 km to the northwest of Wandel Dal (Figure 1), as also seen for the Canadian Lake Hazen case (Ranjbar et al., 2021). A similar abrupt direction shift also occurred with the windspeed increase that produced the down-valley dust observed on 24th April, again linking this dust outbreak to katabatic winds.

The case of up-valley dust occurring at sub-threshold windspeeds on 25th April poses an interesting question (Figure 3a). Bullard et al. (2023) reported episodes of elevated dust concentration associated with up-valley wind directions at relatively low windspeeds from measurements in the Kangerlussuaq valley, possibly from further upwind sources in the same valley, but this is not the case here. The images show active dust emission from Source A, and while dust observed under weaker winds may be indicative of surfaces becoming more susceptible to erosion (where dust can be lifted at lower windspeeds e.g. due to surface drying) a likely explanation is that a single threshold does not characterise adequately the erodibility of the entire source surface (McKenna Neuman, 1993). There is a suggestion that the CARRA reanalysis has under-predicted the windspeeds at the time of dust observation (1800 UTC) on the 25th, or that the work of wind gusts in raising sediment is not reflected in the 3-hourly timestep. Mean windspeeds of similar sub-threshold magnitude (~4-5 m s^{-1}) on preceding days of the 18th and 23rd April did not produce dust, and since the surface on those recent days can be expected to have been of similar erodible potential to its state on the 25th, CARRA may not be representing true wind strength... It is clear overall however that synergistic satellite observations and CARRA reanalysis unambiguously document the role of winds directed both up- and down-valley in raising dust; a characteristic behaviour also seen in other high latitude valley dust sources over longer term field-based studies (e.g. Bullard et al., 2023). The observation of such bi-directional dust activity is significant because the transport direction of the raised dust will influence its impact following eventual downwind deposition; for example as an aquatic nutrient input (Crusius, 2021) or via its effect in albedo-darkening of snow and ice (Oerlemans et al., 2009).

Conclusion

While it is recognised that high latitude locations can be receptors of long-range dust that originated in the low-latitudes (e.g. VanCuren et al, 2012), significance has recently been attached to dust sources active in the high latitudes due to the links between these sources and the fundamental properties of the suspended dust which govern its environmental impacts. For example, both the particle size distribution and geochemistry of dust differ between high latitude locally-sourced dust and that which has undergone a longer residence time in atmospheric transport (e.g, Shi et al., 2020; Barr et al., 2023). For the sources examined here >82°N in Greenland, whilst relatively small in spatial extent, the dust events reported in this study provide clear evidence of the most northerly occurrences of blowing dust phenomena yet observed on Earth. With the absence of meteorological observations from such locations, when high-resolution satellite imagery is coupled with gridded regional reanalysis data, such a combination of weather monitoring can offer insights into the meteorological controls of dust processes that are active in these most extreme and remote latitudes.

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Data Availability

Sentinel-2 and CARRA data are freely available from EU Copernicus sources. The point sources of surveyed candidate dust sources are available by request to the corresponding author.

Author Contributions

Matthew Baddock: Conceptualisation, Writing – Original Draft, Visualisation, Formal analysis, Funding acquisition, Validation, Supervision. Alex Hall: Investigation, Formal Analysis, Data curation, Validation; Joe Rideout: Investigation, Formal Analysis, Data curation, Validation; Rob Bryant: Conceptualisation, Writing – Review and Editing, Visualisation, Formal analysis, Funding acquisition, Supervision, Validation. Jo Bullard: Conceptualisation, Funding acquisition, Supervision, Validation. Santiago Gassó: Conceptualisation, Writing – Review and Editing, Funding acquisition, Supervision.

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Figures

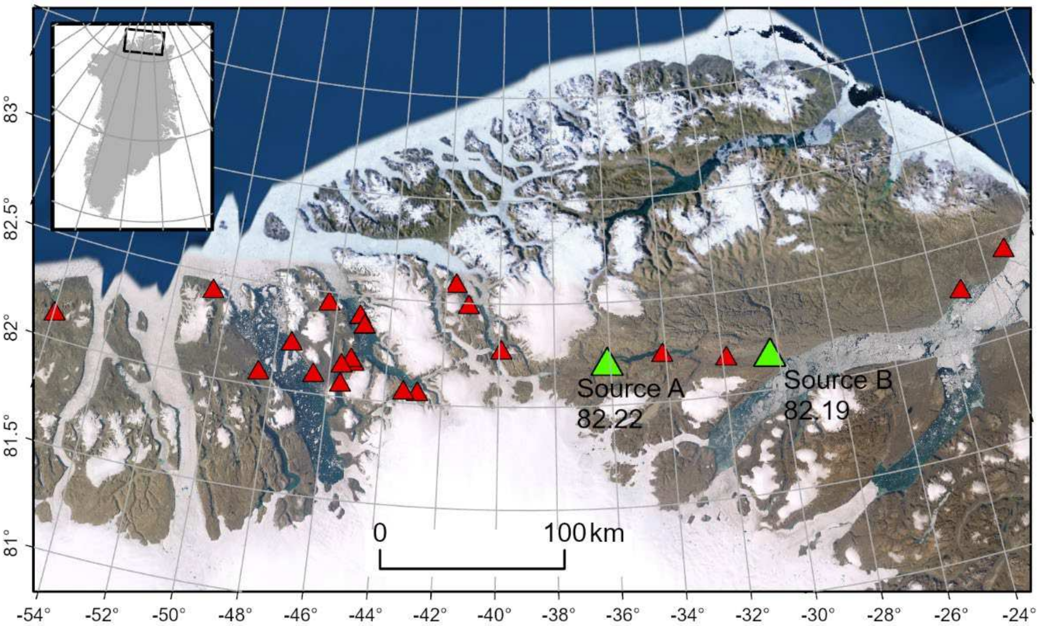

Figure 1: The study area of Peary Land, northern Greenland, showing all candidate dust source locations inspected >82°N. Candidate locations not exhibiting any observable dust activity in the 2016-2022 systematic review of Sentinel-2 imagery are marked red, while the two locations where dust events were observed are green and labelled (Source A and B). Underlying image is the ESRI-provided World Imagery high resolution basemap for 2021-09-1.

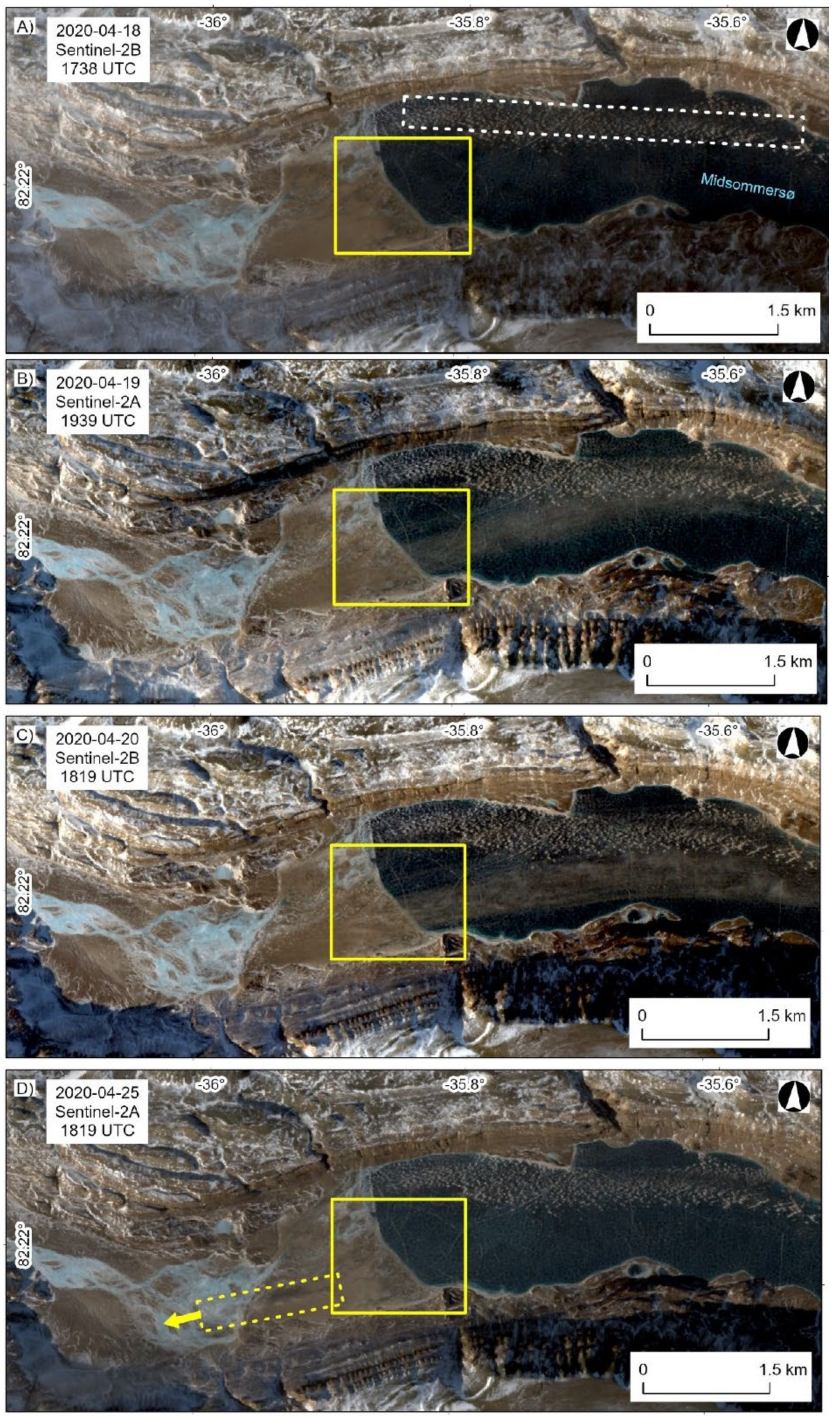

Figure 2: Sentinel-2 true-colour images over Source A for selected days from the focused study period in late April 2020. A) Dust-free scene on April 18th, B) down-valley dust event captured on April 19th, C) well developed dust plume extending over the source-bordering lake (Midsommersø), to the east, April 20th, D) small up-valley directed dust plume (marked by dashed yellow box and arrow) on April 25th The dashed white box in A highlights presence of drifted snow formed on the surface of the frozen lake, with brown appearance likely due to recent previous dust

deposition. The common yellow box highlights the land surface area containing the upwind points of observed dust plumes for comparison with the dust-free scene.

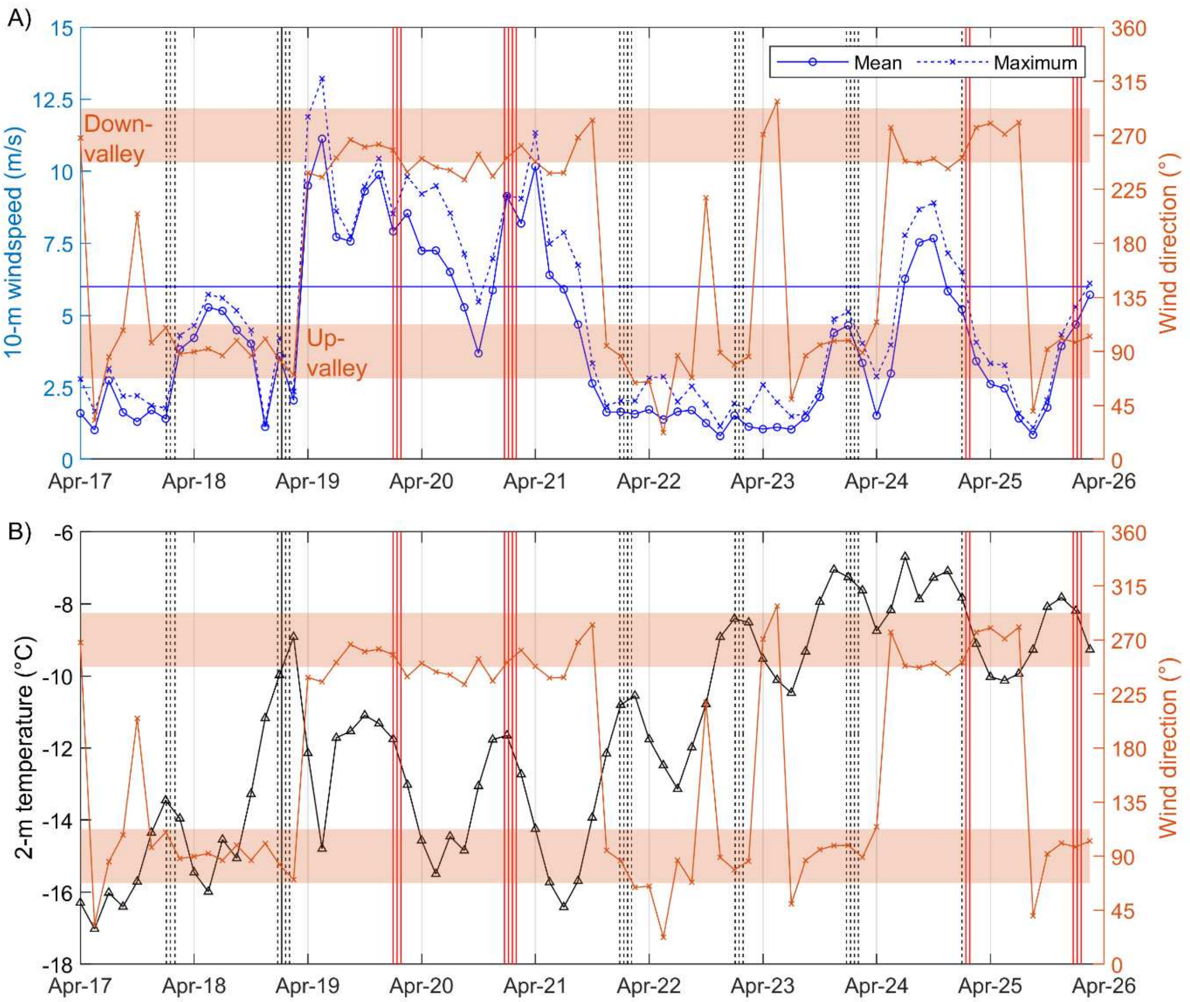

Figure 3: A) Time series of spatially-averaged mean windspeed, single-point maximum windspeed and wind direction all at 10 m, and B) 2-m air temperature together with 10-m wind direction, from 3-hourly CARRA reanalysis, for Source A through the period 17-25th April 2020. The straight horizontal line in the top panel shows a 6 m s^{-1} indicative threshold for aeolian activity. Vertical lines in both panels indicate all overpass times of Sentinel-2A/B, where black dash indicates overpass with no dust plume visible (19), red indicates dust plume visible (12) and black solid indicates a cloud-obscured scene (1). The upper horizontal peach patch highlights

down-valley wind directions from WNW-WSW, and lower patch marks up-valley winds from ENE-ESE.