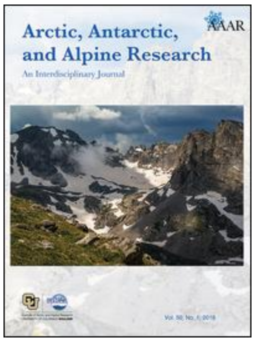

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Seasonal and decadal variability of dust observations in the Kangerlussuaq area, west Greenland

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ABSTRACT
Dust emissions from high-latitude, cold-climate environments have started receiving more attention in the past decade. This is because emission frequency and magnitudes are expected to increase with rising global temperatures, leading to a reduction in terrestrial ice masses and increases in suitable sediment for the aeolian system. Of the identified high-latitude dust source regions, Greenland has received relatively little attention. Using World Meteorological Organization (WMO) dust-code analysis, this study presents a seventy-year record of dust events and preferential dust transport pathways from Kangerlussuaq, west Greenland. A clear seasonal pattern of dust emissions shows increases in dust events in spring and autumn driven by effective winds and sediment supply. The decadal record suggests an increase in the magnitude, but not frequency, of dust events since the early 1990s. Pathways analysis suggests that dust is preferentially transported away from the Greenland Ice Sheet (GrIS) toward the Davis Strait and Labrador Sea. When dust is transported toward the GrIS, it is more likely to be deposited in the ice-marginal ablation zone than on the higher altitude areas of the ice sheet. The impact of dust deposition on terrestrial, cryospheric, and aquatic environments is also discussed.

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Dust; dust code; seasonality

Introduction

The locations and emission patterns of Earth's dust sources are of broad interest because of the impact of sediment deflation on source-area soils (McTainsh and Strong 2007), the effect of dust on meteorological and atmospheric phenomena (Choobari, Zawar-Reza, and Sturman 2014), and the implications of dust following deposition (e.g., Lawrence and Neff 2009; Miller et al. 2016). While most dust emissions are from sources within the subtropical dust belt (Ginoux et al. 2012; Prospero et al. 2002), recent research suggests at least 5 percent of global dust emissions come from sources within the high latitudes (≥50°N ≥ 40°S; Bullard et al. 2016). Although it can affect lower latitudes, most dust originating at high latitudes stays within the high latitudes, and therefore has the potential to affect very sensitive systems within the Arctic (Groot Zwaaftink et al. 2016) and Antarctic.

Eight key high-latitude dust-source regions have been identified: Alaska, Canada, Eurasia, Greenland, Iceland, Antarctica, New Zealand, and Patagonia (Bullard 2017). With the exception of Iceland there have been very few systematic studies of the seasonal variation in dust emissions at high latitudes, nor of long-term variation in the magnitude and frequency of dust events. This article focuses on dust emissions from west Greenland. The ice-free areas of Greenland have long been identified as locally important dust sources (Hobbs 1931, 1942) with dust storms described as reaching >100 m high (Dijkmans and Törnqvist 1991) and potentially causing darkening of the Greenland Ice Sheet by deposition, which may affect albedo and rates of ice melt (Wientjes et al. 2011). Dust input to soils and lakes may also have substantial ecological impacts (Anderson et al. 2017). The aim of this article is to investigate the seasonal and decadal variability of dust emissions in southern west Greenland. The objectives are to:

(1) Determine and explain the seasonal timing of dust events and the seasonal pattern of potential dust transport pathways;
(2) Explore whether there has been any decadal variability in dustiness from 1945 to 2015.

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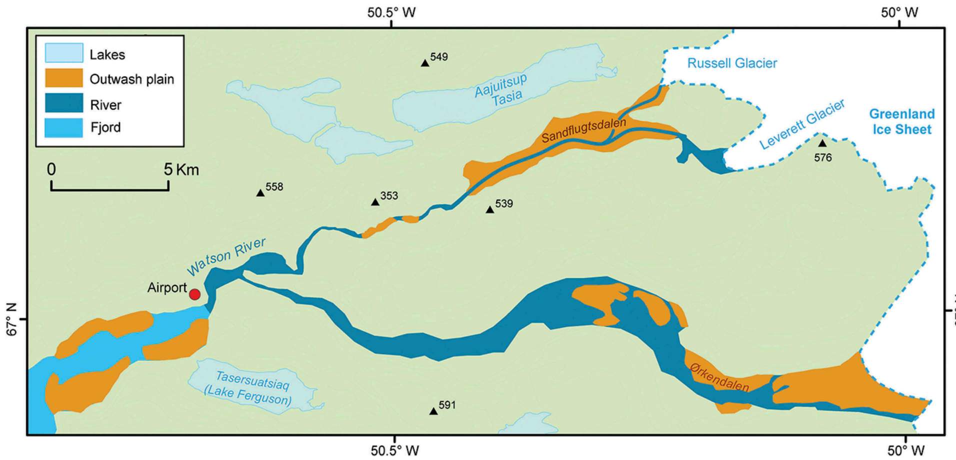

Figure 1. The Kangerlussuaq region indicating location of outwash plains, which are the main dust sources. The WMO station is located at the airport.

The area of interest is that around Kangerlussuaq (67°00′N, 50°43′20”W). For the purposes of this article, the Kangerlussuaq region is considered to extend from the head of the fjord Kangerlussuaq to the west margin of the Greenland Ice Sheet (GrIS; Figure 1). It is representative of the Greenland coastal zone, and geomorphic and stratigraphic mapping have revealed extensive modern aeolian deposits and indicate a close link between glaciofluvial and aeolian activity (Dijkmans and Törnqvist 1991). The three main potential dust sources are the proglacial outwash plains and dunefields in Sandflugtsdalen and Ørkendalen and the sand bars located at the head of the fjord (Bullard and Austin 2011; Figure 1). An additional dust source may be the reworking or erosion of loess deposits (Heindel, Chipman, and Virginia 2015), which extend from the ice sheet to approximately 70 km west. There are also small anthropogenic dust sources close to the head of the fjord, notably localized sand and gravel mining and a golf course.

Methods

Kangerlussuaq has a continental, subarctic climate. Regional mean annual precipitation is <250 mm with very low runoff and a mean annual temperature of −5.1°C (Aebly and Fritz 2009; Mernild et al. 2015). Mean annual evapotranspiration is approximately 300 mm, making the area very dry. There is a strong local precipitation and temperature gradient with distance from the ice sheet that may also affect soil moisture gradients. Overall wind speeds are high but decrease rapidly with increasing distance from the GrIS (Bullard and Austin 2011; Heindel, Chipman, and Virginia 2015). Winds recorded both proximal to the GrIS and 25 km away at Kangerlussuaq airport regularly exceed the threshold for aeolian sediment transport of approximately 6 m s^{-1} (Dijkmans and Törnqvist 1991). Data used in this article are primarily from the World Meteorological Organization (WMO) station at Kangerlussuaq.

Dust-code observations

Weather stations worldwide are used to record surface meteorological observations as defined by the WMO. Included among the observations are records of dust events that are assigned codes reflecting the severity and proximity of the event (Table 1). Such dust codes have been used to explore patterns of dust emissions in Australia (Buckley 1987; McTainsh and Pitblado 1987), China (Lim and Chun 2006), Iceland (Dagsson-Waldhauserova, Arnalds, and Olafsson 2014), Japan (Fujiwara et al. 2007), and Mauritania (Niang, Ozer, and Ozer 2008). For this article dust codes recorded at the WMO station at Kangerlussuaq were the main data source. However, there can be ambiguities and inconsistencies associated with the recording of dust-code data (O'Loingsigh et al. 2010, 2014), and the implications of these for data from this station are considered further on.

There has been a WMO meteorological station at Kangerlussuaq since 1942 (station number 4231), and throughout its operation dust-code data have been recorded. The meteorological station was moved in the early 1970s to its current site at Kangerlussuaq International Airport. For this analysis, we draw on data from 1945 to 2015. Data analysis also suggests that the way in which dust codes are assigned to dust events has changed during this seventy-year period. For

Table 1. World Meteorological Organization (WMO) weather codes relating to dust events.

Synop Code	Weather Description	Total Observations at Kangerlussuaq from 1945 to 2015
06	Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation	75
07	Dust or sand raised by wind at or near the station at the time of observation, but no well-developed dust whirl(s) or sand whirl(s) and no dust storm or sandstorm seen	776
08	Well developed dust whirl(s) or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation, but no dust storm or sandstorm	41
09	Dust storm or sandstorm within sight at the time of observation or at the station during the preceding hour	142
30	Slight or moderate dust storm or sandstorm has decreased during the preceding hour	18
31	Slight or moderate dust storm or sandstorm, no appreciable change during the preceding hour	24
32	Slight or moderate dust storm or sandstorm has begun or has increased during the preceding hour	28
33	Severe dust storm or sandstorm has decreased during the preceding hour	1
34	Severe dust storm or sandstorm, no appreciable change during the preceding hour	1
35	Severe dust storm or sandstorm has begun or has increased during the preceding hour	1
98	Thunderstorm combined with dust storm or sandstorm at time of observation, thunderstorm at time of observation	0

example, prior to 1947 only SYNOP code 6 was recorded, and between 1948 and 1972 only SYNOP code 7 was recorded, whereas from 1973 onward the full range of codes was used. It is unlikely that only code 7 events actually occurred from 1947 to 1972, and instead observers were using code 7 to indicate the presence or absence of dust rather than the full range of codes that indicate the severity of events. In order to maximize the length of record used but circumvent the problems of inconsistent recording, for the purposes of this article the concept of dust event days (DED) is used. Dust event days have been defined in various ways in the literature but are essentially any days on which a dust event has been recorded regardless of type or severity (Lamb et al. 2009). Here a DED is defined as any day when the meteorological station records a dust event using any of the SYNOP codes listed in Table 1, with the exception of code 8. Code 8 events (dust whirls – small dust-carrying vortices) are excluded because they are very spatially restricted and unlikely to mobilize large amounts of dust (Jemmett-Smith et al. 2015).

By using DEDs the analysis is restricted to the frequency of dust events and does not include magnitude of events. However the Dust Storm Index (O'Loingsigh et al. 2014), which does take magnitude of event into account, can be calculated with some confidence for the post-1973 record, and is used to explore recent changes in dustiness.

In both the previous and current location, the WMO station at Kangerlussuaq has been situated a few kilometers distant from dust sources close to the GrIS and at a lower altitude than most of the loess deposits that might contribute to dustiness in the area. It is, however, located close to the head of the fjord and the sand bars that contribute to dust emissions (Figure 2). There are few detailed observations of dust events against which to evaluate the dust-code data set. The event described by Dijkmans and Törnqvist (1991), in which "100 m high dust clouds were transported from the floodplain in the direction of the sand sheets and the uplands" (10), is likely to be have been a code 7 event recorded at the WMO station on September 26, 1987. Engels (2003) observed two dust events at Lake Anna (430 m asl), located 2.3 km north-northwest of the WMO station. The smaller of the two occurred on June 20, 2001, under south-easterly winds but was not recorded at the WMO station and may have been the result of localized deflation of soils. The second event, which occurred on June 23, 2001, was described by Engels as "very large" (2003, 34) and was logged at the WMO station (1400 hrs, code 7; 1800 hrs, code 8). At the start of the event winds were from the east (100°), veering to 240° at the end of the event. The WMO dust-code

Figure 2. Dust entrainment from sediments at the head of the fjord near Kangerlussuaq, west Greenland, July 1, 2014. Photograph courtesy of Tom Matthews.

record is therefore likely to be a reasonably accurate reflection of the frequency of moderate to severe dust events but may underestimate local dust events that are confined up-valley in Sandflugtsdalen and Ørkendalen. It is possible that dust emissions from anthropogenically modified surfaces (sand mine and golf course) may be recorded at the WMO station, but their proximity to the large natural dust source at the head of the fjord makes it impossible to differentiate these.

Wind data and air parcel trajectory modeling

Hourly wind speed and direction data are recorded at Kangerlussuaq WMO station. In this region wind speeds are strongly influenced by distance from the GrIS and wind direction is strongly topographically controlled. The meteorological station is located approximately 25 km from the GrIS and daily mean wind speeds, measured at 10 m above the ground, averaged 3.54 m s^{-1} for the seventy-year period, varying from 0 m s^{-1} to 14.18 m s^{-1}. The meteorological station is located at the head of a fjord aligned east-northeast–west-southwest and downstream of Sandflugtsdalen, which has approximately the same alignment. Wind direction recorded at Kangerlussuaq is bidirectional and strongly controlled by topography. Winds recorded closer to the ice sheet are more directionally variable than at the meteorological station, reflecting the fact that closer to the ice sheet the valley is broader and less topographically constrained than at the head of the fjord (Bullard and Austin 2011).

Possible transport pathways for dust from Kangerlussuaq were analyzed using forward air parcel modeling through the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) tool (version 4; Draxler and Hess 1997, 1998). From a specified location, height, and time, HYSPLIT enables computation of the position of an air parcel as driven by three-dimensional winds at hourly time steps for a user-determined duration. There is no indication of precisely how long dust entrained from sources in the area is likely to remain airborne, because this depends on particle size, wind speed, rainfall, and other meteorological variables. Previous studies of dust from high latitudes have suggested that fine dust fraction could remain airborne for ten days (Neff and Bertler 2015), while models focusing on high-latitude dust dispersion have used atmospheric residence times of 120 days (Groot Zwaaftink et al. 2016). For this study we have used a maximum run of seventy-two hours for two reasons. First, HYSPLIT trajectory accuracy decreases over longer durations (Stohl 1998); second, the shorter time scale increases confidence that the simulated trajectories represent dust in transport, because the particles are less likely to have undergone deposition (wet or dry; Baddock et al. 2017). Using data from Iceland, Baddock et al. (2017) have demonstrated considerable differences between transport patterns based on all days compared to those based only on days when dust was observed. They suggest that these differences may be particularly acute for high-latitude dust-source regions due to the importance of sediment availability as a control on dust activity (Bullard et al. 2016; Nickling 1978). For this analysis air parcel trajectories were only calculated for DEDs with the start time corresponding to the first recorded observation of dust on each day.

Two different run durations were calculated using two different meteorological reanalysis data sets. The first configuration was a twelve-hour run, driven using Global Data Assimilation System (GDAS) daily data at a spatial resolution of 0.5°. These data are only available for the time period 2008–2015, so although the high spatial resolution makes it possible clearly to visualize the trajectories in the immediate area of Kangerlussuaq, the data represent only a short record and a limited number of events (n = 40). The second configuration was a seventy-two-hour run driven by the monthly NCEP/NCAR global reanalysis product at 2.5° resolution (Kalnay et al. 1996) for the twenty years from 1995 to 2015 (n = 141). This allows a regional scale analysis of trajectories, highlighting potential longer distance transport of dust within the Arctic and beyond. The NCEP/NCAR data set is also suggested to be more appropriate for modeling altitudinal profiles of dust at high latitudes than other data sets, such as ERA-40 (Baddock et al. 2017; Harris, Draxler, and Oltmans 2005). The start height for all trajectories was 100 m above ground level. Data are visualized by plotting the percent of trajectory lines or points within grid cells according to the method of Baddock et al. (2017).

Other data

Controls on dust emissions other than wind regime include surface soil moisture, snow cover, and sediment supply. In addition, the threshold for aeolian sediment transport can be moderated by temperature and humidity (McKenna Neuman 2004). Monthly variation in precipitation was determined using modeled gridded precipitation data (1961–1990), taken from the CRU CL V.21 climate model (Mitchell et al. 2004; New et al. 2002) and used as a surrogate for soil moisture. Snow depth (cm) is recorded at the WMO station every two to three days. The main potential dust sources in the Kangerlussuaq area are outwash plains and deposits at the head of the fjord, and conditions in these locations are strongly influenced by meltwater discharge. During high discharge the outwash plains can be inundated, preventing aeolian entrainment. Monthly averaged Watson river discharge (Q) data were calculated from measurements carried out between 2007 and 2013 (Hasholt et al. 2013).

Results and discussion

During the seventy-year record there were 1,107 observations of dust events (all types; Table 1), and there were 389 DEDs.

Seasonality of dust events

Figure 3 shows the seasonal variability of DEDs. Dust can be recorded at any time during the year, but the highest frequency of DEDs is during spring (May, June) and autumn (September, October) and the lowest during the summer months of July and August. Wind speed at the time of the dust observation is variable but typically in the range of 6–10 m s^{-1} at 10 m. From Figure 4 it can be seen that the wind speed associated with a dust event is higher during the spring and summer months than in March or autumn and early winter (September to December).

The occurrence of dust emissions reflects the relative importance and interactions among sediment supply, sediment availability, and transport capacity (Bullard et al. 2011). The aeolian system in many proglacial regions is considered to be supply limited; that is, dust

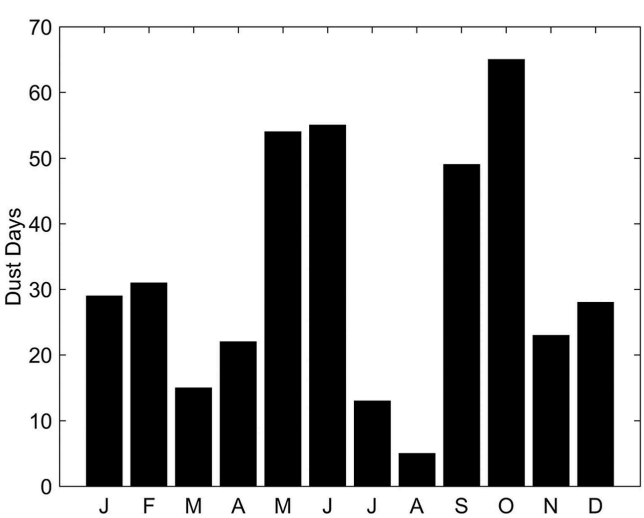

Figure 3. Seasonal variability of dust-event days at Kangerlussuaq (1945–2015).

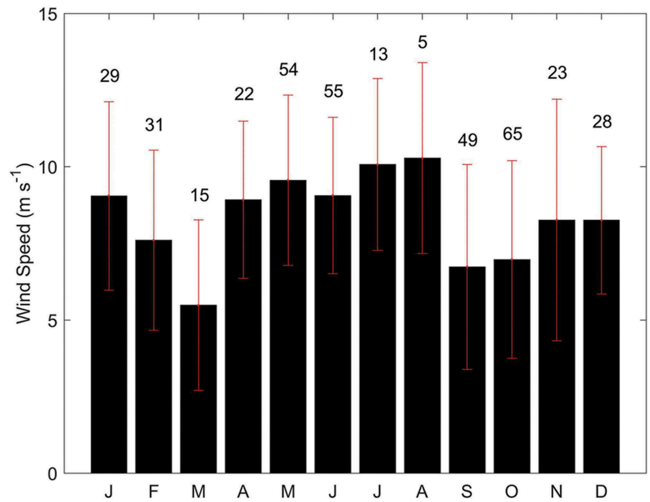

Figure 4. Wind speed at the time of the first dust observation on each DED, averaged per month (1945–2015). Red bar indicates standard deviation. Number above each bar indicates the total number of DEDs in each month from 1945 to 2015.

emissions are limited by a lack of suitable sediment (Bullard 2013). Sediment supply is primarily controlled by fluctuations in meltwater suspended sediment transport and supply to the proglacial floodplain. Deflation from glacial outwash plains may also be availability limited; for example, by surface moisture content, vegetation, snow cover, frost, or the development of lag deposits (McKenna Neuman 1993). Transport capacity is determined by effective wind speed. The controls on supply, availability, and transport capacity are not mutually exclusive, and it is the interaction of these drivers that determines the seasonality of dust emissions at both low (Bullard et al. 2011) and high (Bullard et al. 2016) latitudes. Figure 5 shows that peak dust emissions in Kangerlussuaq occur in spring when snow cover is rapidly decreasing, exposing the sediment that is delivered to the outwash plains to strong winds. As meltwater discharge increases during the summer a large proportion of the outwash plains may be inundated, reducing deflation potential; at the same time, precipitation increases during the summer, raising surface moisture levels across the landscape and suppressing dust emissions. As discharge and precipitation decrease at the end of the summer (September–October) a large quantity of fine sediment can be left draped across the outwash plains and is susceptible to wind erosion. Snow cover increases during the autumn and winter and may protect sediments from deflation, although it is spatially discontinuous and generally thin (Willemse 2002). Temperature, which is not included in Figure 5, averages approximately −20°C in the winter months, rising to 10° C at the height of summer, but shows considerable interannual variability.

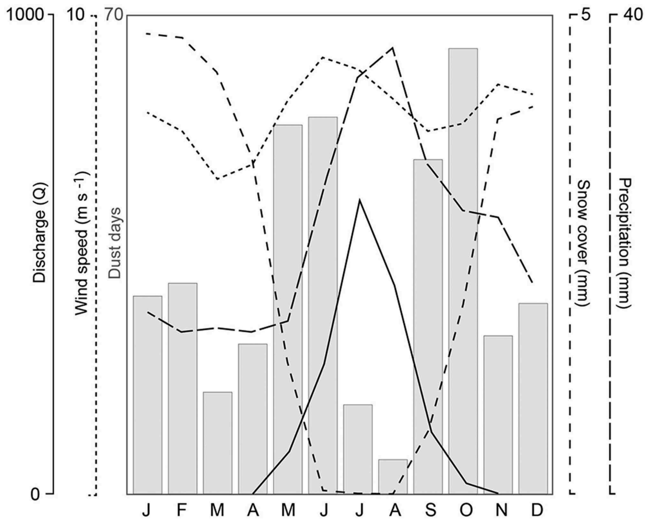

Figure 5. Seasonal variability in DEDs and selected variables affecting dust emission. Dust days = total number of DEDs per month (1945–2015). Average monthly snow cover (mm) and wind speed (m s^{-1}) recorded at Kangerlussuaq (1945–2015). Modeled monthly precipitation data (see text for details). Average monthly discharge (1997–2013; Hasholt et al. 2013).

The seasonality of dust emissions identified in this part of west Greenland is similar to that in other high-latitude areas, such as Canada, New Zealand, and Patagonia, which all have two peaks—one in spring and the second in autumn (Bullard et al. 2016). The impact of cold conditions on aeolian sediment transport is complex and not clearly understood (Barchyn and Hugenholtz 2012). Hobbs (1942) suggested that strong winds may drive winter dust storms in Greenland. At Kangerlussuaq, average monthly wind speed and maximum gusts are no higher during the winter than during the summer; however, wind speeds on DEDs are strong, particularly in January. Low temperatures may increase the effectiveness of the wind by reducing the threshold for aeolian transport (McKenna Neuman 2004), but conversely the exposure of frozen soils at the surface can increase the threshold (Wang et al. 2014). The relationship between DED and wind speed suggests that stronger winds are needed to entrain dust during winter months compared to spring and autumn. Similarly, strong winds are also needed to entrain dust during the summer months of July and August. During the seventy-year period only five DEDs were recorded during August, and these were associated with an average wind speed of 10.3 m s^{-1}. By comparison the forty-nine DEDs recorded during September were associated with an average wind speed of 6.7 m s^{-1}. August is the month during which the highest amount of rainfall occurs during the year, and the increase in threshold velocity is likely to be because of high surface moisture content increasing particle cohesion and the seasonal increase in annual plant cover (McKenna Neuman 1993).

Variations in sediment supply can also affect the magnitude and frequency of dust events. At the seasonal scale, these can be linked to variations in meltwater discharge and suspended sediment supply (Bullard 2013). For example, spring meltwater events with a high suspended sediment concentration can deposit large amounts of fine material on the glacial outwash plains (McGrath et al. 2010) that, once desiccated, can blow away as dust events (Bullard and Austin 2011). Suspended sediment concentration is seasonally and annually quite variable (Hasholt et al. 2013), and occasional high-magnitude, low-frequency events, such as jökulhlaups, may also affect sediment supply to dust storms (Prospero, Bullard, and Hodgkins 2012, see later discussion).

Dust transport pathways

Wind direction at the Kangerlussuaq WMO station is strongly bidirectional, aligned with the fjord/valley orientation. Figure 6 shows the seasonal variability of wind direction for all winds from 1945 to 2015. Wind is primarily down valley, with a resultant wind direction toward the west-southwest. During spring and summer months, up-valley winds can occur. The WMO station is located west of the main outwash plain sources in Sandflugtsdalen and Ørkendalen where wind is more directionally variable (Bullard and Austin 2011; Heindel, Chipman, and Virginia 2015). The wind rose in Figure 7 shows the average wind speed and direction over the seventy-year period for DEDs only. This suggests that wind associated with recorded dust events has a stronger easterly component than that for all winds. Some of the strongest winds are recorded as southwesterly and are likely to entrain sediments at the head of the fjord and transport them toward the GrIS.

The distance and direction in which dust might travel was modeled for twelve-hour dust-day trajectories (2008–2015) using the HYSPLIT model with the GDAS 0.5° daily reanalysis data set (Figure 8). Data are displayed as the percentage of trajectory lines passing through a 0.5° grid cell. The greatest concentration of trajectories is at the head of the fjord and the dominant pathway of air parcels is to the northwest, away from the GrIS toward the Davis Strait. Very few trajectories indicate dust transport onto the GrIS, but some skirt the edge of the ice sheet as they travel northward.

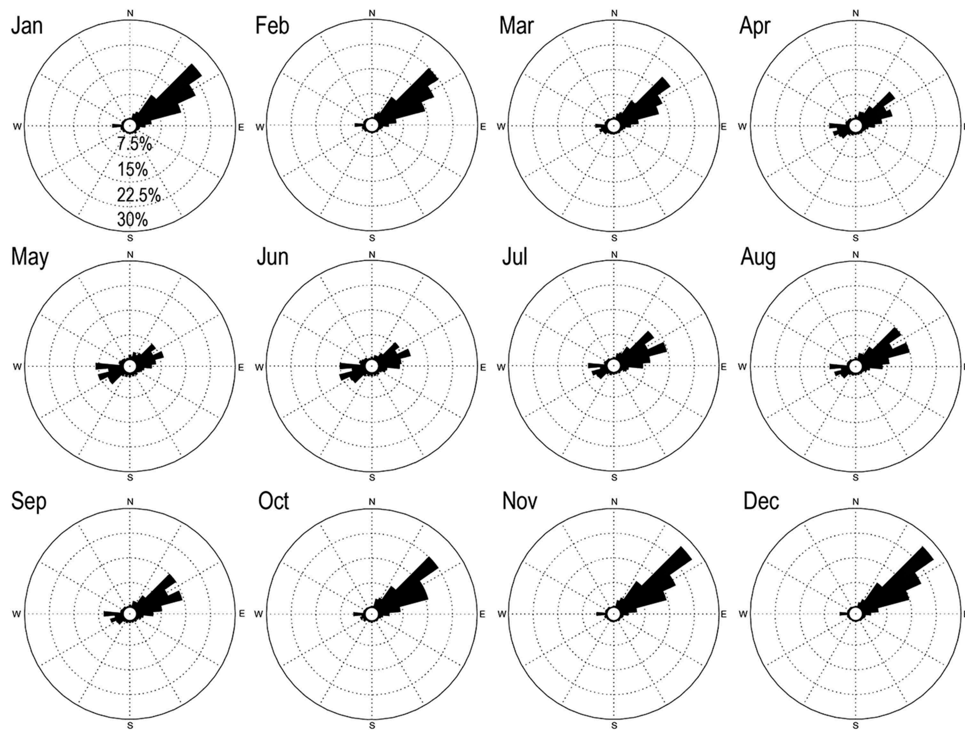

Figure 6. Monthly wind roses for all winds (1945–2015) recorded at Kangerlussuaq.

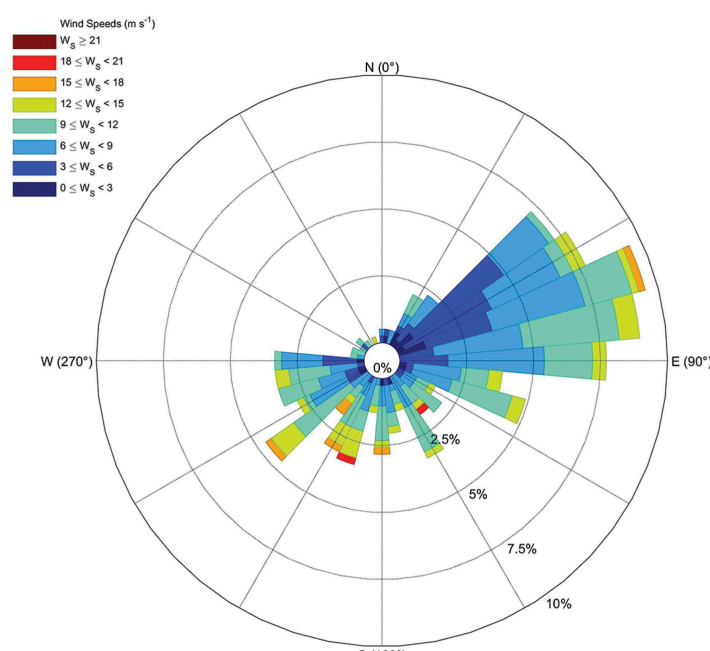

Figure 7. Wind direction and speed calculated for DEDs only (1945–2015).

The gridded trajectory-line densities for seventy-two-hour runs (1995–2015) support the twelve-hour, high spatial resolution analysis and indicate that a significantly higher proportion of air parcels associated with dust days travel west into the North Atlantic Ocean and Davis Strait rather than onto the GrIS (Figure 9). Figure 10 shows the altitudinal distribution of the air parcel trajectories, which were all started at 100 m asl. The majority (77.3%) of air parcels remain at or below 100 m in the atmosphere, with only 15.4 percent reaching 100–500 m and very few reaching altitudes above 500 m (4.5%) or 1,000 m (2.8%). Of the trajectories that are located at less than 100 m, most are concentrated in the

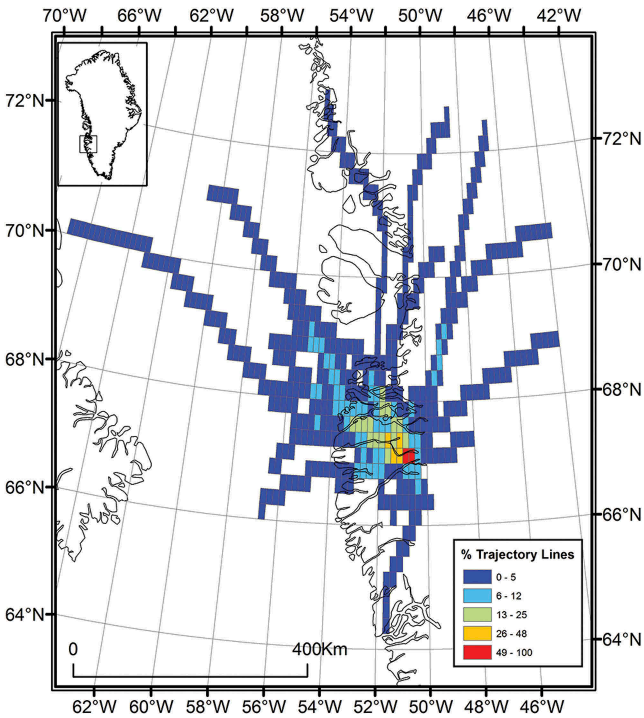

Figure 8. Trajectory line density (% trajectories per 0.5° × 0.5° cell) for twelve-hour HYSPLIT simulations run at 100 m start height using GDAS daily data for DEDs during 2008–2015.

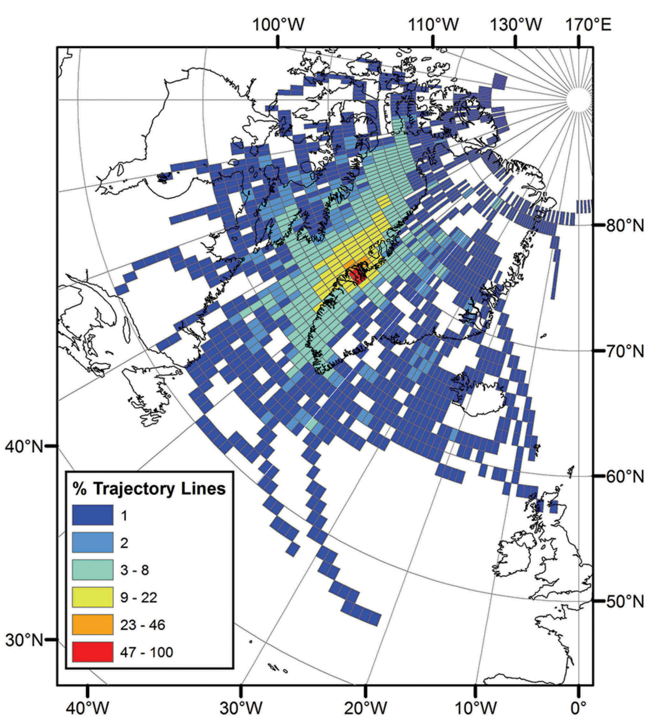

Figure 9. Trajectory line density (% trajectories per 1° × 1°cell) for seventy-two-hour HYSPLIT simulations run at 100 m start height using NCEP/NCAR data DEDs during 1993–2015.

North Atlantic Ocean and Davis Strait and tend to skirt the edge of the GrIS. Where trajectories reach more than 500 m, the vast majority of these are located to the east of Kangerlussuaq around the margin of the GrIS.

The distribution of dust sourced from southern west Greenland suggested here is in agreement with Groot Zwaaftink et al. (2016), who indicated that locally derived dust was unlikely to be deposited in the center of the GrIS. This is likely because stable Arctic air parcels are not aided by thermal uplift (Arnalds, Dagsson-Waldhauserova, and Olafsson 2016; Baddock et al. 2017; Groot Zwaaftink et al. 2016) and are unable to transport dust onto the ice sheet, other than around the margins. This result may be influenced by the low spatial resolution of the NCEP/NCAR input data (Baddock et al. 2017; Harris, Draxler, and Oltmans 2005); however, the spatial distribution of dust driven by the two data sets used here is very similar.

Decadal variability in dust storm frequency (1945–2015)

The long-term record from 1945 to 2015 in Figure 11 highlights the interannual variability of dust observations and dust-event days. The average number of dust-event days is five per year, but zero observations were made during four years (1962, 1971–1973). There are notable peaks in both dust observations and dust days in 1963 (eighty-three observations, eighteen DEDs) and 1985 (125 observations, twenty-three DEDs).

Although Figure 11 suggests that the frequency of dust observations and DEDs has increased during the seventy-year record (e.g., comparing the 1950s with the 1980s), as previously discussed, there is more confidence in the post-1973 dust-code record than in that for earlier decades. There is no systematic increase in the frequency of occurrence of dust observations post-1973, but the extreme peak during 1985 is worth a more detailed examination. On an annual-decadal scale, occasional increases in the magnitude and/or frequency of dust storms have been associated with large pulses of sediment delivered to glacial outwash plains by jökulhlaups (Bullard 2013; Dijkmans and Törnqvist 1991; Prospero, Bullard, and Hodgkins 2012). A number of jökulhlaups have been observed in the Kangerlussuaq region, the best-documented being in 1984, 1987, 2007, 2008, and 2010 (Mikkelsen et al. 2013; Russell 1989; Russell et al. 2011; Sugden, Clapperton, and Knight 1985), all of which affected the Watson River. The jökulhlaup in 1984 occurred on October 10 and 11 and might explain the peak in dust observations and DEDs in 1985, although from Figure 12 it can be seen that the dust observations were primarily during winter months (January and December 1985) and may have been the result of strong

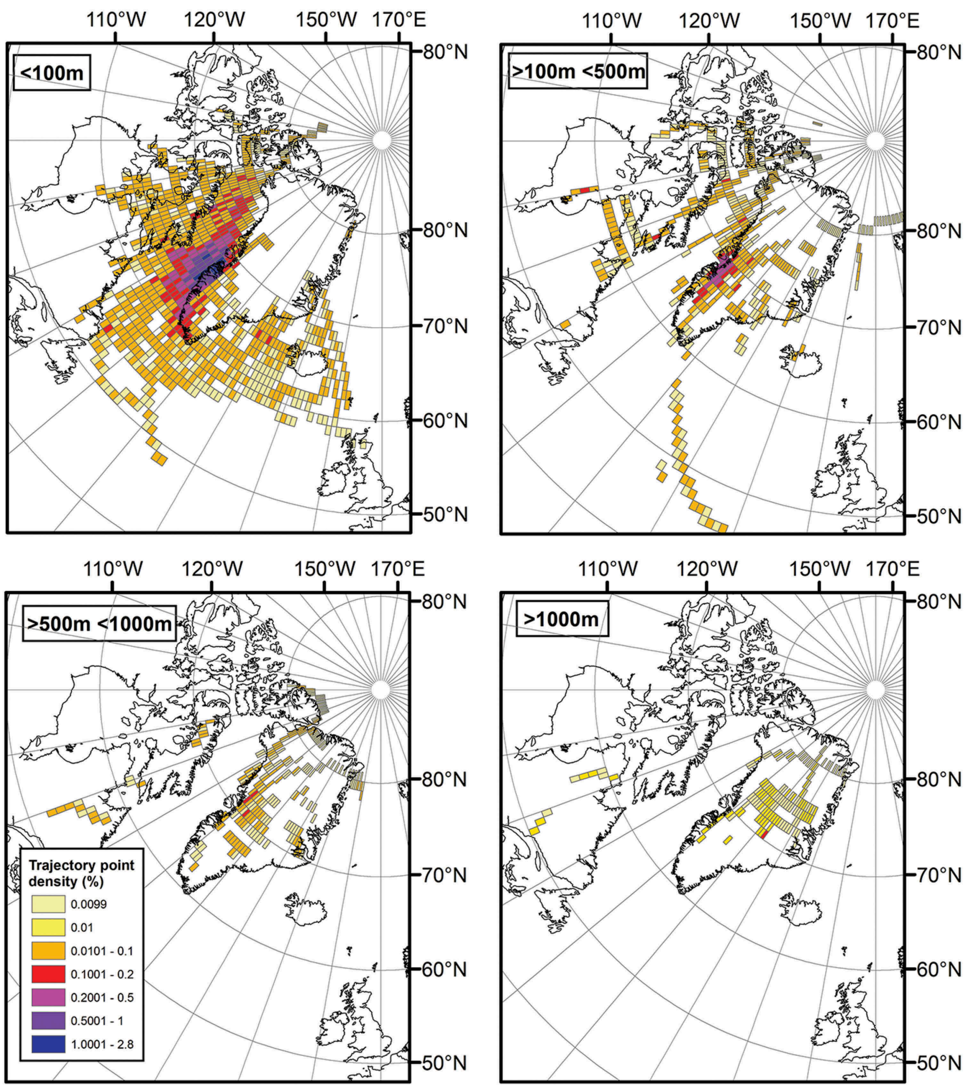

Figure 10. Trajectory point density (% per 1° × 1°cell) at different altitudes for seventy-two-hour HYSPLIT simulations run at 100 m start height using NCEP/NCAR data for DEDs from 2008 to 2015.

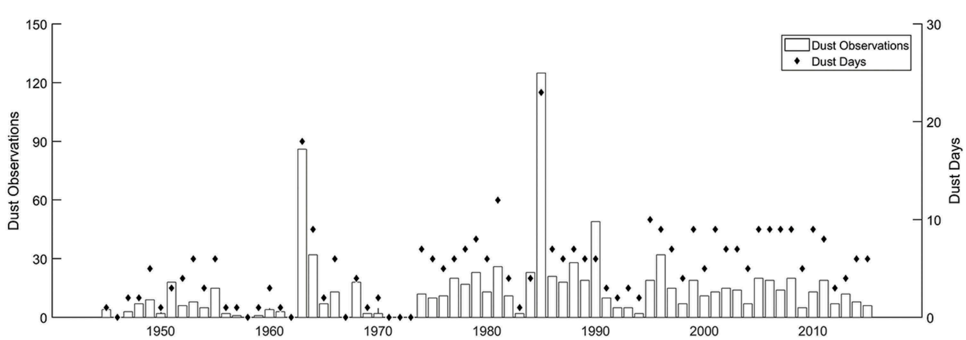

Figure 11. Annual total dust observations and DEDs for 1945–2015 recorded at Kangerlussuaq.

winds rather than just sediment supply. In addition, temperatures in January and December 1985 were relatively mild and above freezing on several days, which may have contributed to increased sediment availability related to snow melt or sublimation. There are no marked dust peaks following the jökulhlaups in 1987 (July 18), 2007 (August 31), 2008 (August 31), or 2010. The lack of a consistent relationship between jökulhlaups and subsequent dust events likely reflects the range of variables controlling sediment supply and

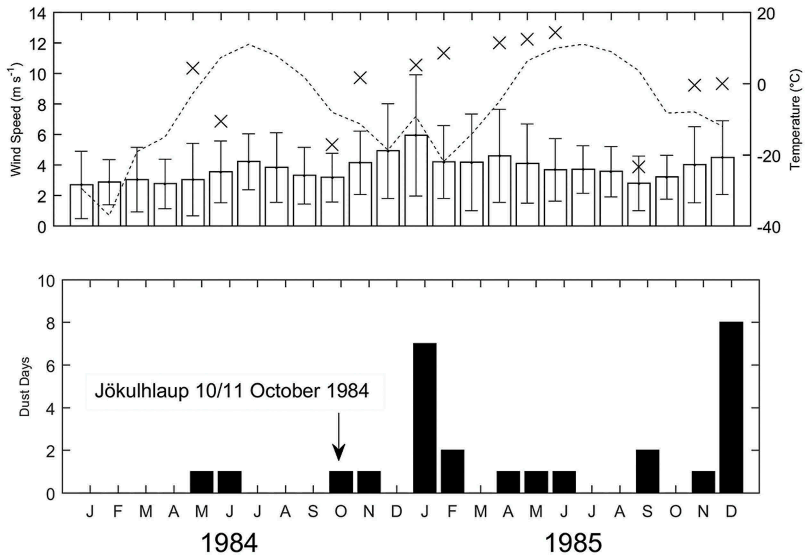

Figure 12. (A) Average monthly wind speed for 1984 and 1985. Bars show average wind speed and standard deviation for all days. Dotted line is average monthly temperature; X indicates average wind speed for DEDs only. (B) Total DEDs per month for 1984 and 1985.

availability; for example, sediment loadings in these drainage events are quite variable (Mikkelsen et al. 2013).

Variations in magnitude of dust emissions (1973–2015)

The long-term record explored so far only examines the frequency of dust emissions and not the magnitude. A large dust storm is more likely to generate a substantial amount of dust that is transported long distances than a short-lived local event. The magnitude and frequency of dust events were examined using the Dust Storm Index (O'Loingsigh et al. 2014) for the post-1973 record, which suggests that the annual severity of dust emissions was higher during the decade 2000–2010 than during the preceding decades (Figure 13). This is not because of an increase in the frequency of dust events, but, rather, an increase in the number of severe dust events (codes 33–35) compared to the 1980s and 1990s.

As outlined previously, dust-storm magnitude and frequency are driven by the interplay of variables affecting sediment supply, availability, and transport capacity. Sediment supply is primarily controlled by meltwater delivery from the ice sheet to the outwash plains. Kamenos et al. (2012) recorded a trend of increasing runoff in west Greenland since the mid-1980s, concomitant with an increase in atmospheric temperature (Mayewski et al. 2014), but there was no significant increase in

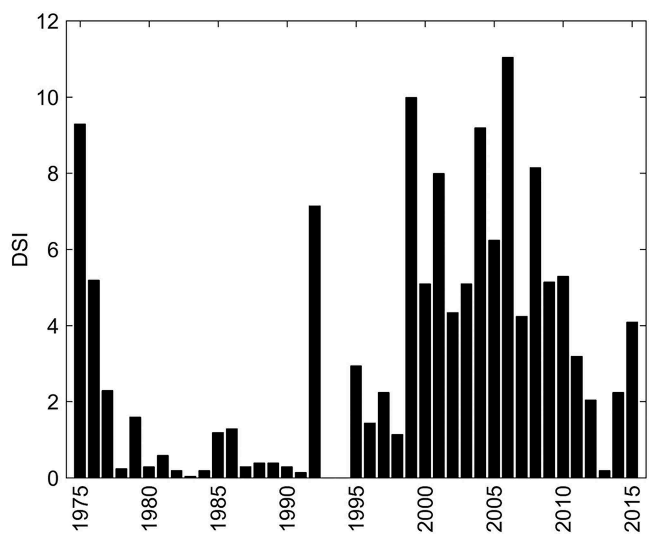

Figure 13. Dust Storm Index calculated for 1973–2015.

suspended sediment concentration to the fjord (2000–2012; Hudson et al. 2014). The lack of a relationship between runoff and suspended sediment concentration is not unusual (Jansson, Rosqvist, and Schneider 2005) and may be because of variation in the timing of meltwater events, subglacial drainage patterns, as well as the occurrence of high-magnitude, low-frequency events such as jökulhaups (Hasholt et al. 2013). The increase in atmospheric temperature may have increased sediment availability by decreasing soil moisture on the floodplains, but the balance between factors that promote or decrease sediment availability is complex, spatially quite variable (Bullard 2013), and requires further research.

Implications of dust deposition

This article has focused primarily on the frequency of dust emissions and the potential transport pathways along which dust from sources in the Kangerlussuaq area might travel and be deposited. To date, there have been no event-specific or year-round measurements of contemporary dust emissions or deposition around Kangerlussuaq, which makes it difficult to estimate the magnitude of any local or regional impact. It is possible, however, to consider the types of impact that dust deposition might have and its implications for different local systems.

Anderson et al. (2017) discuss how the glacier, terrestrial, and aquatic systems in Kangerlussuaq are linked and highlight the potentially pivotal role that aeolian dust deposition can play in facilitating the transfer of sediments and nutrients between these systems. Cumulative modern dust-deposition rates around Kangerlussuaq have been estimated using records from upland peat mires at 70 g m^{-2} yr^{-1} (Willemse et al. 2003). Many Arctic lakes are low-resource, nutrient-poor systems where ecological structure and function is highly controlled by nutrient supply (Bonilla, Villeneuve, and Vincent 2005). Where the lakes are nitrogen and phosphorous co-limited and require a source of phosphorous to support production increases, dry deposition of dusts may be an important input to the ecological system, because it is typically enriched in phosphorous (Brahney et al. 2014; Lawrence and Neff 2009). Input of dust to alpine lakes (Brahney et al. 2014; Mladenov et al. 2011) has received some attention but its impacts are not well understood for Arctic lakes. There is a need to understand better how much dust is received by lakes, the biogeochemical characteristics of the dust, and also the impact of the timing of dust input on lake ecological response. For example, the results presented here suggest that dust emissions occur throughout the year, in which case dust deflated and deposited during the winter will accumulate in lake ice and in snow packs and be deposited as a large pulsed input to the water at the start of the melt season. In contrast, dust deposited after ice-off during the late spring, summer, and early autumn is more likely to provide regular but low-magnitude inputs; these magnitude-frequency patterns may influence the ecological response (Bullard 2017).

Dust can also contribute to soil formation in proglacial areas, but its role may vary with distance from the dust source. High rates of dust deposition and relatively coarse aeolian sediment limit or retard soil formation very close to the source. As dust-deposition rates and sediment size decrease with distance from the dust source, soil development increases. Muhs et al. (2004) found that soils in Alaska were best developed 10–25 km distant from the loess source and where the sand and coarse silt (>20 μm diameter) component comprises less than 60 percent and the fine silt (2–20 μm) component more than 30 percent of the particle size distribution. In southern west Greenland, Dijkmans and Törnqvist (1991) examined particle size variation in loess deposits along a transect westward from near the Russell Glacier along the ridge (300–400 m asl) to the north of Sandflugtsdalen. They found that the proportion of sand and coarse silt (>32 μm) dropped from about 80 percent to 70 percent over 4 km distance and was about 65 percent a further 20 km away at Kangerlussuaq airport. This is considerably finer than the surface sediments on the outwash plains (Dijkmans and Törnqvist 1991) but in a similar range to those in active aeolian transport along the valley floor (Bullard and Austin 2011), suggesting that strong winds have transported the sands and coarse silts onto the ridge more than 100 m above the floodplain.

It has been shown that dust particles play an important role in the cryosphere by increasing ice albedo (Krinner, Boucher, and Balkanski 2006; Oerlemans, Giesen, and van den Broeke 2009), affecting the timing of snowmelt (Painter et al. 2012; Skiles et al. 2012) and providing sediment for cryoconite development (Cook et al. 2016). Analysis of wind directions and HYSPLIT forward trajectories indicates that the dominant direction of dust events is away from the GrIS. In the spring, a change from unimodal to bimodal winds promotes transport of material toward the GrIS and corresponds with the dustiest months. If particles are transported to the ice, they are likely to be deposited on the edges of the ice sheet in the ablation zone because HYSPLIT forward trajectories suggest that the dust pathways skirt the edge of the GrIS. The restriction of dust deposition to the margins of the ice sheet is most likely because of a lack of thermal uplift of particles, meaning that they cannot rise to a sufficient altitude to deposit on the upper ice sheet (Baddock et al. 2017). In the ablation zone, dust is likely to affect snow and ice melt. Painter et al. (2012) suggested that dust deposition during the spring and summer months would accelerate snowmelt via an increase in albedo and the accelerating growth of snow grains, whereas in the winter dust particles are likely to be buried by periodic snow events, limiting the time that the particles are at the surface. Because of the seasonal changes in wind direction in Kangerlussuaq, dust particles are only likely to be transported toward the GrIS during the spring, when they are most likely to play a larger role in the glacial system.

Recent work has suggested that dust can be an important source of iron to high-latitude oceans, although the relative importance of iron from aeolian deposition compared to fluvial input in coastal waters is as yet unclear (Crusius et al. 2011; Winton et al. 2014). Near Kangerlussuaq, the ecological impact of dust deposition on the fjord waters is likely to depend on whether it is input to the relatively fresh surface waters in the inner fjord (0–70 km from the head of the fjord) or into the saline outer fjord water (Nielson et al. 2010). The HYSPLIT trajectories indicate that dust may be transported over the Davis Strait and could potentially trigger phytoplankton blooms in the ocean. Whether the quantity of material required actually reaches the ocean is unclear and, as with dust deposition to lakes, the timing of the dust input can be important, because the phytoplankton response will depend on available light levels (Crusius et al. 2011).

Conclusion

This work presents the first long-term assessment of dust emissions from southern west Greenland. Dust emissions occur all year round but peak in spring and early autumn. This coincides with the reduction of factors affecting sediment availability (snow cover, precipitation) and an increase in effective transport capacity. The evidence linking increased dust emissions to preceding jökulhlaup events is somewhat inconclusive and requires further exploration. The decadal record suggests that dust-storm magnitude may have increased from 1985 to the 1990s, however, further work is required to characterize the magnitude of dust events at source. The study also presents preferential dust-event pathways from Kangerlussuaq, indicating that the majority of events travel toward the Davis Strait and Labrador Sea. Pathways toward the GrIS can occur during spring, where the wind direction shifts from unimodal to bimodal; however, events often skirt the edges of the ice sheet instead of traveling toward the upper ice sheet. The impact that dust deposition may have on glacial, fluvial, oceanic, and lacustrine environments will depend on the quantity of material deposited and the timing of deposition. More research is required to understand the linkages between these environments and how ongoing changes in climate may affect this system.

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