



Increased North Atlantic dust deposition linked to Holocene Icelandic glacier fluctuations

Helena Stewart,¹ Tom Bradwell,¹ Joanna Bullard,²  Robert D McCulloch^{3,4} and Ian Millar⁵

The Holocene
2023, Vol. 33(2) 231–237
© The Author(s) 2022



Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/09596836221131697
journals.sagepub.com/home/hol



Abstract

Mineral dust concentrations are coupled to climate over glacial-interglacial cycles with increased dust deposition occurring during major cold phases over the last ~100 ka. Holocene records suggest considerable spatial and temporal variability in the magnitude, frequency and timing of dust peaks that reflects regional or local drivers of dust emissions and transport. Here, we present stratigraphical, geochemical and isotopic evidence for dust deposition from two high-resolution peat sequences 200 km apart in northern Scotland spanning the last c. 8200 years. ϵ Nd isotope data suggest the dominant minerogenic dust source switches between a low latitude (likely Saharan) and a high latitude, Icelandic source. Marked peaks in increased minerogenic dust deposition at: c. 5.4–5.1, 4.0–3.9, 2.8–2.6, 1.0 and 0.3 ka BP occur against a backdrop of low dust deposition during the mid-Holocene (c. 5.0–4.0 ka BP) and increased background levels of dust during the neoglacial period (<4.0 ka BP). These dust peaks coincide with periods of glacial advance in Iceland and heightened storminess in the North Atlantic. Isotope data for additional dust peaks at c. 1.0 and 0.7 ka BP and the last ~50 years suggest these reflect increased dust from the Sahara associated with aridity and land-use change in North Africa during the Late-Holocene, and modern anthropogenic sources. This work highlights the complexity of Holocene records of dust deposition in the North Atlantic and emphasises the role of dynamic sub-Polar glaciers and their meltwater systems as a significant dust source.

Keywords

palaeoclimates, peat archives, radiogenic isotopes, Scotland, tephrochronology

Received 13 June 2022; revised manuscript accepted 23 August 2022

Introduction

Mineral dust concentration is coupled to climate over glacial-interglacial cycles (Lambert et al., 2008). Increased dust is associated with major cold phases (stadials) characterised by aridity, low terrestrial biomass, increased availability of fine sediments and strong winds at mid-latitudes (Muhs et al., 2013). This has allowed terrestrial, marine and cryospheric records of aeolian dust deposition to be used as proxies for both palaeoclimate and atmospheric transport pathways (Maher et al., 2010). While atmospheric dust concentrations have been lower during the Holocene than at the Last Glacial Maximum (28–19 ka BP), considerable fluctuations in the abundance and characteristics of deposited aeolian material have been recorded (e.g. Albani et al., 2015; Kylander et al., 2016; Vanneste et al., 2016). Holocene dust records are variable in terms of their spatial and temporal expression, and strongly reflect regional or local (rather than global) drivers such as glacier dynamics (Bullard, 2013), vegetation change (Egerer et al., 2017), proglacial geomorphology (Sugden et al., 2009), aeolian activity (Humphries et al., 2017) and anthropogenic impact (Hooper and Marx, 2018).

This paper focuses on Holocene records of minerogenic dust deposition in the North Atlantic. Mineral dust is an important part of Earth's biogeochemical cycle and a vital source of micronutrients to marine and terrestrial ecosystems (Bullard et al., 2016; Hawkings et al., 2014). Windblown dust can travel thousands of kilometres but contemporary direct measurements indicate most

is deposited within 1000 km of the source (Lawrence and Neff, 2009). The dominant source of dust to the North Atlantic is the Sahara (Ginoux et al., 2012) from which dust is transported west to the Americas or north towards western Europe (Muhs, 2013). Palaeoenvironmental records suggest mid-Holocene dust deposition in the low latitude North Atlantic and off the northwest coast of Africa was low, associated with the Mid-Holocene African Humid Period and greening of the Sahara; dust deposition then increased (NW Africa) or stabilised (equatorial Atlantic) during the Late-Holocene (e.g. Albani et al., 2015). Under present conditions, Saharan dust can reach the mid- to high latitude North Atlantic and has been recorded in Ireland, the UK, Iceland and mainland Scandinavia (Dall'Osto et al., 2004; Ryall et al., 2002; Varga et al., 2021).

¹Biological & Environmental Sciences, University of Stirling, UK

²Geography and Environment, Loughborough University, UK

³Centro de Investigación en Ecosistemas de la Patagonia, Chile

⁴School of GeoSciences, University of Edinburgh, UK

⁵British Geological Survey, UK

Corresponding author:

Joanna Bullard, Geography and Environment, Loughborough University, LE11 3TU, UK.

Email: j.e.bullard@lboro.ac.uk

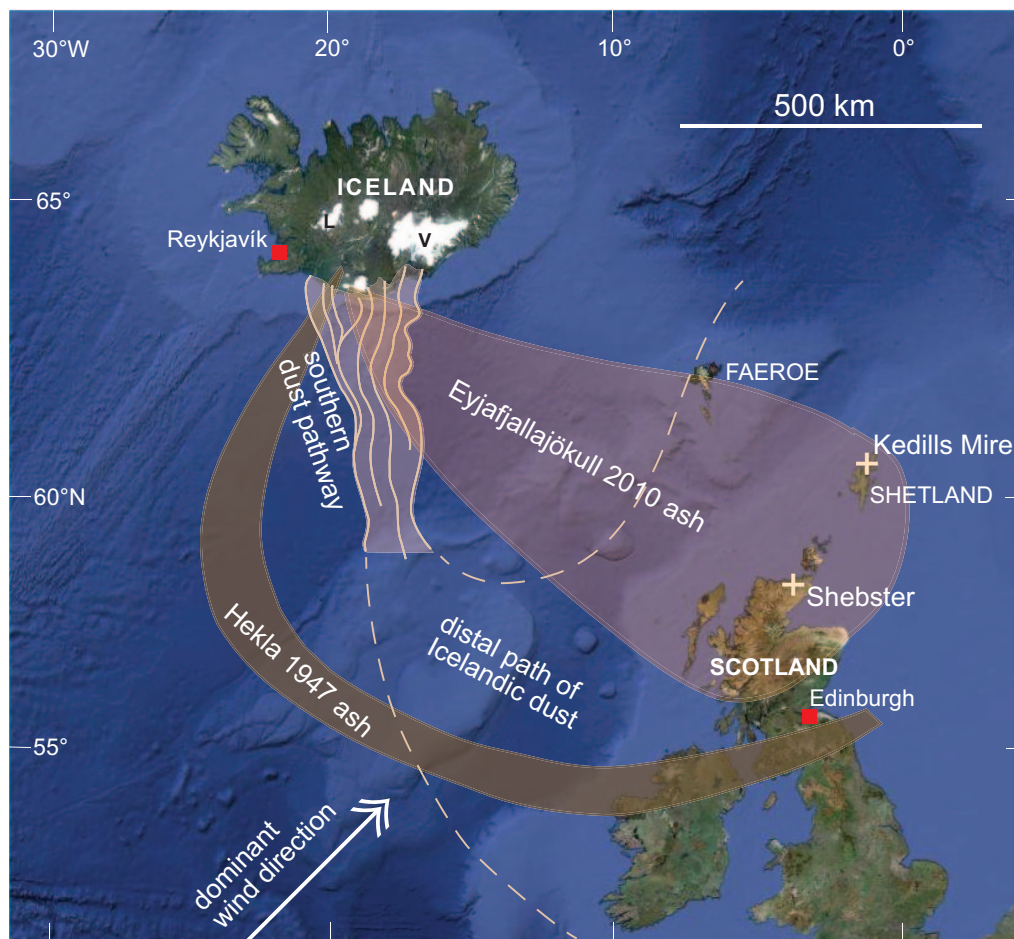


Figure 1. Map of NE Atlantic region showing location of field sites in northern Scotland (Shebster and Kedills Mire), major dust pathways and recent volcanic ash pathways from Iceland (Prospero et al., 2012). Base map imagery: Google Maps.

Around the mid-latitude North Atlantic, increased aeolian activity recorded in sediment archives has been linked to Holocene cold periods in central Greenland and winter storminess in southern Scandinavia (Björck and Clemmensen, 2004; Jackson et al., 2005; Kylander et al., 2016) associated with expansion of the polar vortex or intensified meridional airflow (O'Brien et al., 1995). Within these palaeo-environmental records, regional (100–1000 km) and local (<10 km) aeolian inputs typically dominate. Iceland is a contemporary major source of dust to the North Atlantic (Prospero et al., 2012) and recent accelerated retreat of Iceland's ice caps and ongoing glacio-fluvial activity result in high dust emissions estimated at 4.6 (Groot Zwaafink et al., 2016) to 40 Tg/year (Arnalds et al., 2016). At present Icelandic dust is transported throughout the mid- to high latitude North Atlantic and has been recorded in Svalbard (Moroni et al., 2018), Greenland (Drab et al., 2002) and Ireland (Ovadnevaite et al., 2009).

In this paper we detail the first terrestrial archive of Icelandic Holocene dust deposition in Scotland and examine linkages between mineral dust deposition, Icelandic glacier fluctuations and climate change/storminess in the North Atlantic. We hypothesise that the quantity and distribution of Icelandic dust emissions is likely to have fluctuated during the Holocene in parallel with (or in response to) glacial activity. Modelling and air-parcel trajectory analysis indicate clear dust transport pathways from Iceland to northern Scotland (Baddock et al., 2017; Groot Zwaafink et al., 2016) where the climate is strongly influenced by North Atlantic storms driven by the seasonal position of the polar front jet stream. There are extensive areas of peat in northern Scotland

from which continuous and sensitive indicators of dust load and dust source, alongside climate proxy data, can be extracted and analysis of these peat records is used to test our hypothesis. Icelandic tephra have also been identified in Scotland's peat bogs and provide important chronological marker horizons (Dugmore et al., 1995).

Methods

The minerogenic aeolian dust record was isolated in two peat profiles, where fluvial sediment inputs were topographically excluded, and local accumulation solely comprised of organic matter (Figure 1). The Shebster mire (N58°33'06.6", W003°42'39.0", altitude 82 m) is located in northern Caithness and underlain by Middle Devonian sandstone of the Big-house Formation (Auton et al., 2005). Kedills Mire (N60°41'12.8", W001°02'52.8", altitude 67 m) is a blanket mire on the island of Yell, Shetland underlain by Moine psammite (metamorphosed sandstone and siltstone).

Continuous peat cores (to 6.08 m depth at Shebster and 4.26 m depth at Kedills Mire) were sampled using a 1 m, 75 mm diameter, Russian D-section corer (Jowsey, 1966) and aligned by depth from the surface datum. Cores were sealed in lay-flat tubing and stored at a constant 4°C. Contiguous 2 cm³ samples were acid digested to isolate the minerogenic material (Dugmore et al., 1992) which was analysed using an Olympus BX43 light microscope at 400× magnification.

Atmospheric dust comprises particles deflated from a surface that travel by suspension and may include mineral particles and

Table 1. Conventional radiocarbon ages, calibrated age ranges (Calib ver 8.2 Stuiver and Reimer, 1993), and modelled age ranges for Kedills Mire and Shebster peat records. The IntCal20 calibration curve was applied (Reimer et al., 2020) and deposition model performed using Bacon ver 2.5.5 (Blaauw and Christen, 2011), as described in the main text.

| Laboratory code | Depth (cm) | Material | ^{14}C year BP (1σ) | $\delta^{13}\text{C}_{\text{VPDB}}\%$ | Unmodelled (calibrated) age range (95.4%) cal year BP ¹ | Modelled (calibrated) age range (mean) at 95.4% confidence (cal year BP) ² |
|-----------------|------------|------------|---------------------------------------|---------------------------------------|--|---|
| Kedills Mire | | | | | | |
| SUERC-63942 | 40 | Bulk peat | 649 ± 35 | -28.1 | 555–669 | 94–(200)–310 |
| Hekla AD1158 | 120.5 | n/a | n/a | n/a | 792 | 786–(792)–797 |
| SUERC-63936 | 193 | Bulk peat | 1172 ± 37 | -27.7 | 974–1176 | 1116–(1223)–1301 |
| SUERC-63935 | 243 | Bulk peat | 1821 ± 35 | -29.1 | 1622–1823 | 1648–(1772)–1920 |
| Glen Garry | 265 | n/a | 2120 ± 60 | n/a | 1936–2308 | 1989–(2166)–2327 |
| Kebister | 330.5 | n/a | 3550 ± 50 | n/a | 3695–3975 | 3671–(3844)–4010 |
| Hekla 4 | 344.5 | n/a | 3826 ± 12 | n/a | 4151–4290 | 4103–(4194)–4289 |
| SUERC-63934 | 390 | Bulk peat | 4352 ± 36 | -28.0 | 4845–5036 | 4847–(4947)–5191 |
| SUERC-63933 | 426 | Bulk peat | 5027 ± 35 | -28.7 | 5660–5896 | 5387–(5681)–5846 |
| Shebster | | | | | | |
| Beta – 251972 | 150 | Wood frag. | 1740 ± 40 | -28.3 | 1570–1819 | 1540–(1644)–1786 |
| Beta – 251973 | 271 | Wood frag. | 3010 ± 40 | | 3166–3368 | 3040–(3206)–3346 |
| Hekla 4 | 346 | n/a | 3826 ± 12 | n/a | 4151–4290 | 4105–(4194)–4286 |
| Beta – 251974 | 406 | Wood frag. | 4110 ± 40 | -29.4 | 4579–4838 | 4629–(4779)–4865 |
| Beta – 251975 | 500 | Wood frag. | 5730 ± 40 | -25.6 | 6410–6647 | 6358–(6509)–6645 |
| Beta – 251976 | 612 | Wood frag. | 7530 ± 50 | -24.7 | 8198–8412 | 7988–(8226)–8392 |

resuspended volcanic ash as well as other natural and anthropogenic particles (Pye, 1987). Icelandic aeolian sediments are known to include both glacio-fluvial material and resuspension of material deposited following volcanic eruptions (Arnalds et al., 2016). To investigate the relationship between glacial activity and dust emissions we excluded deposits associated with direct volcanic emissions. The mineral dust residue was classified visually by its morphological characteristics and its abundance was measured using a quantitative percentage-based score (Terry and Chilinger, 1995). Particle-size analysis using a Beckman-Coulter LS280 shows 59%–100% of mineral particles (by volume) are <20 µm diameter which is consistent with long distance atmospheric transport (Stuut and Prins, 2014) although larger particles can also be transported considerable distances (Varga et al., 2021). Cryptotephra layers were identified during analysis of the mineral residue based on morphology, vesicularity and isotropism of glass shards under plane-polarised light. In Scotland cryptotephra layers are extremely thin and unlikely to be locally remobilized on a peat bog. Tephra layers were identified by the peak concentration of the glass component, geochemically identified to a specific Icelandic eruption (Dugmore et al., 1995) and used as isochrones. We can not fully separate tephra minerals from mineral dust but excluded volcanic glass from the measurements of dust abundance to ensure the peak in mineral dust layers could not be caused by tephra. This approach is likely to underestimate total dust deposition. The major element geochemical composition of each tephra sample was categorised by electron microprobe analysis using the SX100 Cameca Electron Microprobe at The University of Edinburgh (Hayward, 2012). A minimum of 10 tephra shards were analysed to provide a representative geochemical signature (Hunt and Hill, 1993). Correlation of the cryptotephra layers to previously dated volcanic eruptions was facilitated by TephraBase (Newton, 1996).

Five samples from the Shebster core were radiocarbon dated using Accelerated Mass Spectrometry (AMS) and supplemented by the identification of the Hekla 4 tephra layer. Five samples were AMS dated from the Kedills Mire core and supplemented by the Hekla 4, Kebister, Glen Garry and Hekla 1158 tephra layers. Calibrated Bayesian age-depth models are used to constrain both

dust records using Bacon (Blaauw and Christen, 2011) and the IntCal20 radiocarbon calibration curve (Reimer et al., 2020) (Table 1).

The Earth's crust and mantle have distinct ranges of isotopic ratios owing to their different mineral assemblages. Iceland almost exclusively comprises young volcanic rocks and has a strong geochemical signature from the upper mantle with relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Scotland is geologically much older, formed predominantly of terrane fragments of continental crust with higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Banner, 2004). To identify the provenance of dust peaks in the cores radiogenic isotope analysis was conducted at the Geochronology and Tracers Facility (formerly part of the NERC Isotope Geosciences Laboratory), British Geological Survey, Keyworth. Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and neodymium (ϵNd) isotope composition was measured using a Thermo Scientific Triton thermal ionisation mass spectrometer, and a Thermo Scientific Neptune + plasma ionisation mass spectrometer, respectively. Strontium data were obtained for both cores. However, neodymium data could only be obtained for the Kedills Mire core as concentrations were too low to be measured in the Shebster core (Supplemental Table S1. Detailed analytical methods are presented in supplementary material).

Results and discussion

We compared the radiogenic isotope data from Kedills Mire to potential dust sources in Iceland, North Africa and China, local Shetland basement rock and other dust isotope records (Figure 2). The $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd isotope data plot on an unusual trend, with ϵNd values ranging from -6.90 to +4.87 at a high, near constant $^{87}\text{Sr}/^{86}\text{Sr}$ value of c. 0.72. This trend cannot be explained simply by mixing of dust derived from available geological sources and must involve a process leading to an increase in the radiogenic Sr component. Jung et al. (2004) and Garçon et al. (2014) discuss the effects of mineralogical sorting and grain size issues on $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (finer-grained fractions have higher $^{87}\text{Sr}/^{86}\text{Sr}$ values) as well as the effect of weathering (materials subjected to higher degrees of chemical weathering have lower $^{87}\text{Sr}/^{86}\text{Sr}$ values). It is likely that the observed Sr-isotope compositions reflect transport

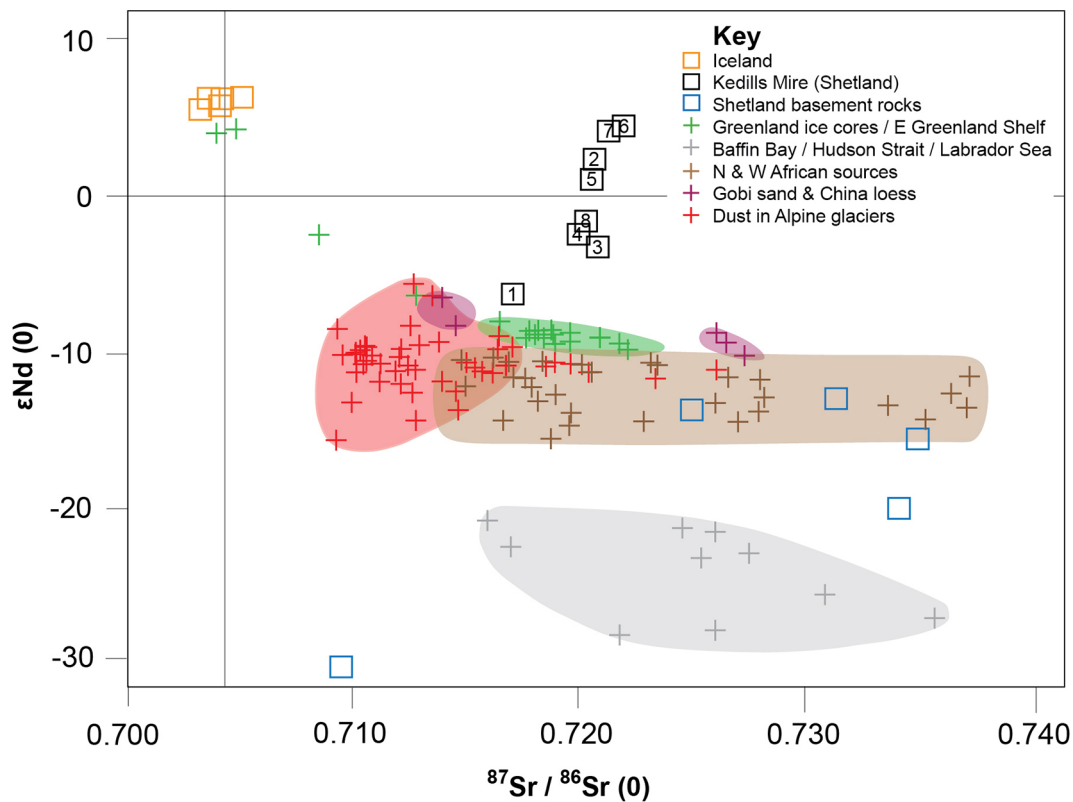


Figure 2. Sr and Nd isotopic data for Iceland (Farmer et al., 2003 and this study), Kedills Mires (numbered points correspond to the sampled dust peaks in Figure 3) and Shetland base rocks (Walker et al., 2016). The isotopic signatures of other regional dust sources are taken from Thevenon et al. (2012). Uncertainties on the new data are smaller than the plotted datapoints, and are as follows: $^{87}\text{Sr}/^{86}\text{Sr}$: ± 0.000043 , Epsilon Nd: ± 0.3 (both 2 SD).

of fine-grained material in an aeolian environment. The samples analysed, which span multiple years, are likely to reflect mixed inputs at the decadal scale but dominant regional sources can be identified associated with particular time periods (Figures 2 and 3). We interpret samples from Kedills Mire with positive ϵNd values as dominated by an Icelandic isotopic signature, suggesting episodic periods of higher dust load in the North Atlantic related to climate-driven environmental changes.

The stratigraphic analyses of dust abundance at the two sites show distinct episodes of higher (peak) dust deposition separated by longer periods of reduced dust input (Figure 3).

The basal peak in dust at Shebster (c. 8.1 ka) coincides with the end of a period of regional rapid climate change (RCC) between c. 9.0 and 8.0 ka (Mayewski et al., 2004). However, we cannot exclude mixing from the underlying minerogenic lacustrine sediment into the lowermost basal peat layers and so this event is treated with caution. There is a period of sustained higher dust input at Shebster, between c. 7.7 and 6.9 ka. The absence of radiogenic isotopic data prevents identification of the source of this dust peak. However, this is a quiescent period during the Holocene thermal maximum, with Icelandic glaciers probably at their minimum extent, making an Icelandic source unlikely. Coinciding with the African Humid Period, this dust peak is also unlikely to originate from the Sahara, although it is broadly contemporaneous with a major dust peak in central Europe (Le Roux et al., 2012) suggesting a third, as yet unidentified regional source of dust at this time.

There is a very large and sustained period of dust deposition at Kedills Mire between c. 5.4 and 5.1 ka. The basal dust (c. 5.7–5.5 ka) may have been derived from local substrate, indicated by the negative ϵNd value (–1.75). However, the large dust peak at Kedills Mire between c. 5.4 and 5.1 ka yielded a positive ϵNd value (4.60) and coincides with an increase in Na+

(deepening of the Icelandic low) and Ca⁺ (increased dust flux) in the GISP2 Greenland ice core and a phase of increased North Atlantic storminess (Stewart et al., 2017). The dust peak recorded at Shebster at c. 5.2 ka is smaller in magnitude and duration and may reflect the different trajectories of dust coming from the north (Baddock et al., 2017). Icelandic glacier and lake sediment records (Figure 3) suggest this period of increased dust deposition occurred at the start of the mid-Holocene transition which ushered in the onset of Neoglaciation in Iceland and elsewhere. Mountain glaciers in central and southern Iceland grew, coalescing to form embryonic ice caps, as the regional snowline descended between c. 5.5 and 5.0 ka (Geirsdóttir et al., 2009; Kirkbride and Dugmore, 2006). This accords with other regional records suggesting this time interval was a period of RCC more widely in the Northern Hemisphere (Mayewski et al., 2004). We note the likelihood that most evidence for renewed ‘neoglaciation’ has not been preserved in the Icelandic glacial landform record owing to removal or censure by subsequent erosional (glacial and fluvial) events.

During a quiescent period lasting approximately 1000 years, between c. 5.0 and 4.0 ka, low dust deposition is recorded in both peat cores and coincides with a prolonged period of positive NAO and reduced North Atlantic storminess during the second half of the mid-Holocene transition (Stewart et al., 2017). At Kedills Mire this period is ended by a brief dust peak at c. 4.0–3.9 ka followed by a sustained rise in background dust levels between c. 4.0 and 1.8 ka punctuated by numerous short dust peaks. At Shebster a significant dust peak is also recorded at c. 4.0–3.9 ka but this manifests as a brief interruption to the Mid-Holocene quiescent phase which continues to c. 3.4 ka. The c. 4.0–3.9 ka event was too short for radiogenic isotopic analysis, but it coincides with a phase of RCC, deepening Icelandic low and a wider signature of Icelandic glacier growth as neoglaciation continued. Hereafter,

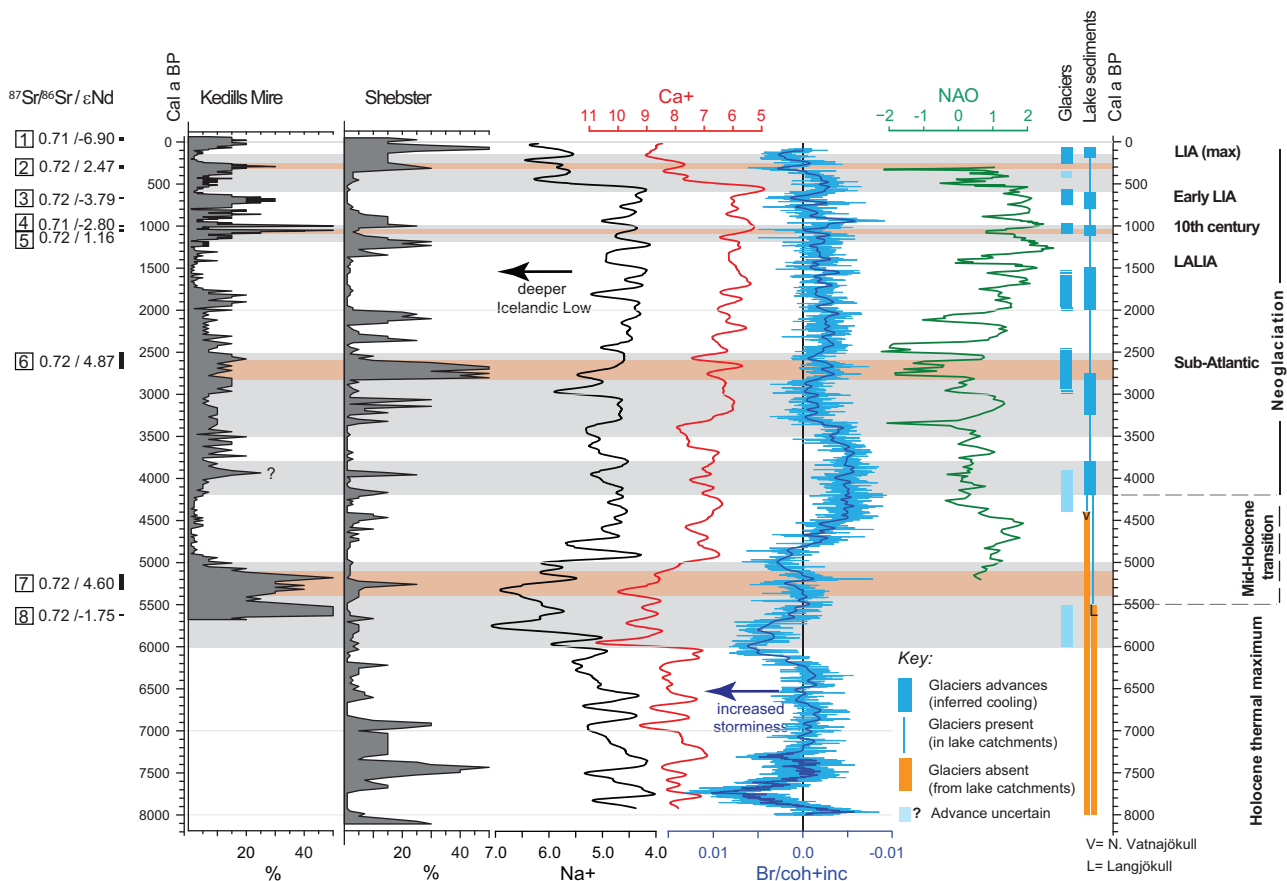


Figure 3. Dust abundance estimates from Kedills Mire (Shetland) and Shebster (Caithness) alongside: Na⁺ (sea salt) and Ca⁺ (dust) from the GISP2 Greenland ice core. Increased levels of Na⁺ and Ca⁺ are associated with periods of more intense and expanded polar circulation and deepening of the Icelandic low (i.e. generally colder intervals) (Mayewski, 1999); Bromine record from Shebster as a proxy for storminess (Stewart et al., 2017); reconstructed 5000-year NAO index based on a lake-sediment core in SW Greenland (Olsen et al., 2012); periods of Holocene glacier advance in southern-central Iceland. Glacial records are compiled from (LIA = Little Ice Age, LALIA = Late Antique Little Ice Age): Dugmore and Sugden (2008), Gudmundsson (1997), Kirkbride and Dugmore (2001, 2006), Schomacker et al. (2012), Geirsdóttir et al. (2009), Ingólfsson Norðdahl and Schomacker (2010), Hannesdóttir et al. (2015) Lake records are compiled from Geirsdóttir et al. (2007), Larsen et al. (2011, 2012), Striberger et al. (2012). The Kedills Mire dust events that have a positive εNd signature are highlighted by brown shaded bars. Periods of rapid climate change (RCC) (Mayewski et al., 2004) are indicated by grey shaded bars.

the dust records at Kedills Mire and, to a lesser degree, Shebster are characterised by higher background levels of dust and a greater frequency of dust peaks in both cores.

The largest sustained dust peak recorded at Shebster at c. 2.8–2.6 ka occurs during the latter part of a RCC period between c. 3.5 and 2.5 ka (Mayewski et al., 2004). There is a concomitant increase in dust at Kedills Mire, but not of the same magnitude, and the associated εNd value is the highest (i.e. most similar to Iceland) for the whole record (4.87). Icelandic glaciers advanced significantly between c. 3.0 and 2.5 ka, some reaching their Holocene maxima (Geirsdóttir et al., 2009). This coincided with a sustained shift to a negative NAO index (Olsen et al., 2012), although the GISP2 Na⁺ and Ca⁺ curves do not record marked changes in North Atlantic atmospheric pressure systems (Mayewski, 1999).

A ~500-year quiescent period occurs in the Kedills Mire record between c. 1.8 and 1.3 ka, with minimal dust deposition at both sites coinciding with reduced North Atlantic storminess, a benign Icelandic Low (in GISP2 data) and a generally neutral NAO index. We relate this period of low dust flux to the centuries between the Roman Warm Period (c. 2.3 and 2.0 ka) and Mediaeval Climate Anomaly (1.2–0.7 ka) (Patterson et al., 2010) when Iceland's glaciers were significantly smaller than in the preceding millennium and atmospheric circulation was generally stable across northern Europe (Geirsdóttir et al., 2009).

Between c. 1.2 ka and present there is an increase in the frequency and magnitude of dust peaks recorded at Kedills Mire and

Shebster. Dust peaks at c. 1.1 and 0.3 ka (at Kedills Mire) coincide with periods of RCC and significant glacier fluctuations in Iceland during the 10th Century and Little Ice Age (LIA). These dust peaks also have positive εNd values (i.e. more Icelandic). However, there are peaks that occur outside of the RCC periods (c. 1.0 and 0.7 ka) with negative εNd values, resulting in a marked switch from a positive to negative εNd values in less than ~100 years. We suggest that this variability reflects the high-frequency, high-amplitude, possibly high-seasonality, climatic changes experienced in the North Atlantic region during the last 1.5 ka (Hernández et al., 2020; Patterson et al., 2010). The dust record at Shebster remains high during the LIA and into the 20th century but the uppermost dust peak at Kedills Mire (mid-20th century to present day) has the most negative εNd value of the entire record which probably reflects 20th century anthropogenic environmental change and a variety of dust sources (Fagel et al., 2014).

Conclusion

Iceland is a substantial source of mineral dust to the North Atlantic which could play an important role in ocean fertilisation and enhanced marine productivity. This paper reconstructs the Holocene dust deposition records from two peat bogs in northern Scotland 200 km apart and demonstrates that the mineral dust originates from both low-latitude, probably Saharan, and high-latitude, probably Icelandic, sources. Our well-dated record

indicates that during the mid-Holocene climate transition and neoglacial periods (centred c. 5.2 and 2.7 ka respectively) the dominant dust source was Iceland, with dust peaks reflecting periods of glacier expansion, driven by climate change, and borne by strong North Atlantic winds. From c. 1.1 ka onwards the frequency of dust peaks increases, with the dominant source switching from the Sahara (c. 1.0–0.6 ka) to Iceland since c. 0.3 ka in response to renewed Little Ice Age glaciation and a more vigorous Icelandic Low-pressure system. Finally, modern (mid-20th century onwards) mineral dust deposition may reflect anthropogenic activity from a range of different sources.

Acknowledgements

We would like to thank Dr Andrew Finlayson, Dr Nicholas Golledge, Dr Mary McCulloch, Natasha Rolph and James Blaikie for valuable assistance in the field.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: HS was supported by a NERC-BUFI – University of Stirling joint studentship (NE/K501156/1). RMcC is supported by ANID R20F0002 (PATSER). The Natural Environmental Research Council Radiocarbon Facility (SUERC) provided radiocarbon support: 1879.0415 and the authors would particularly like to thank Dr Pauline Gulliver for her help in the processing of the radiocarbon samples.

ORCID iD

Joanna Bullard  <https://orcid.org/0000-0002-2030-0188>

Supplemental material

Supplemental material for this article is available online.

References

- Albani S, Mahowald NM, Winckler G et al. (2015) Twelve thousand years of dust: The holocene global dust cycle constrained by natural archives. *Climate of the Past* 11: 869–903.
- Arnalds O, Dagsson-Waldhauserova P and Olafsson H (2016) The Icelandic volcanic aeolian environment: Processes and impacts — A review. *Aeolian Research* 20: 176–195.
- Auton CA, Gillespie MR, Lott GK et al. (2005) *Palynological and Petrological Constraints on Correlation of Devonian Strata Across the Downreay district: bgs Commissioned Report CR/05/009*. Edinburgh: British Geological Survey.
- Baddock MC, Mockford T, Bullard JE et al. (2017) Pathways of high-latitude dust in the North Atlantic. *Earth and Planetary Science Letters* 459: 170–182.
- Banner JL (2004) Radiogenic isotopes: Systematics and applications to earth surface processes and chemical stratigraphy. *Earth-Science Reviews* 65: 141–194.
- Björck S and Clemmensen LB (2004) Aeolian sediment in raised bog deposits, Halland, SW Sweden: A new proxy record of holocene winter storminess variation in southern scandinavia? *The Holocene* 14: 677–688.
- Blaauw M and Christen JA (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6: 457–474.
- Bullard JE (2013) Contemporary glacial inputs to the dust cycle. *Earth Surface Processes and Landforms* 38: 71–89.
- Bullard JE, Baddock M, Bradwell T et al. (2016) High-latitude dust in the Earth system. *Reviews of Geophysics* 54: 447–485.
- Dall'Osto M, Beddows DCS, Kinnersley RP et al. (2004) Characterization of individual airborne particles by using aerosol time-of-flight mass spectrometry at mace Head, Ireland. *Journal of Geophysical Research Atmospheres* 109: D21302.
- Drab E, Gaudichet A, Jaffrezou JL et al. (2002) Mineral particles content in recent snow at Summit (Greenland). *Atmospheric Environment* 36: 5365–5376.
- Dugmore AJ, Larsen G and Newton AJ (1995) Seven tephra isochrones in Scotland. *The Holocene* 5: 257–266.
- Dugmore AJ, Newton AJ, Sugden DE et al. (1992) Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. *Journal of Quaternary Science* 7: 173–183.
- Dugmore AJ and Sugden DE (2008) Do the anomalous fluctuations of Sólheimajökull reflect ice-divide migration? *Boreas* 20: 105–113.
- Egerer S, Claussen M, Reick C et al. (2017) Could gradual changes in holocene Saharan landscape have caused the observed abrupt shift in North Atlantic dust deposition? *Earth and Planetary Science Letters* 473: 104–112.
- Fagel N, Allan M, Le Roux G et al. (2014) Deciphering human–climate interactions in an ombrotrophic peat record: REE, Nd and Pb isotope signatures of dust supplies over the last 2500 years (Misten bog, Belgium). *Geochimica et Cosmochimica Acta* 135: 288–306.
- Farmer GL, Barber D and Andrews J (2003) Provenance of Late Quaternary ice-proximal sediments in the North Atlantic: Nd, Sr and Pb isotopic evidence. *Earth and Planetary Science Letters* 209: 227–243.
- Garçon M, Chauvel C, France-Lanord C et al. (2014) Which minerals control the Nd–Hf–Sr–Pb isotopic compositions of river sediments? *Chemical Geology* 364: 42–55.
- Geirsdóttir Á, Miller GH and Axford Y (2009) Holocene and latest pleistocene climate and glacier fluctuations in Iceland. *Quaternary Science Reviews* 28: 2107–2118.
- Geirsdóttir Miller G H and Andrews J T (2007) Glaciation, erosion and landscape evolution of Iceland. *Journal of Geodynamics* 43: 170–186.
- Ginoux P, Prospero JM, Gill TE et al. (2012) Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Reviews of Geophysics* 50: RG3005.
- Groot Zwaafink CD, Grythe H, Skov H et al. (2016) Substantial contribution of northern high-latitude sources to mineral dust in the Arctic. *Journal of Geophysical Research Atmospheres* 121: 13678–13697.
- Gudmundsson HJ (1997) A review of the holocene environmental history of Iceland. *Quaternary Science Reviews* 16: 81–92.
- Hannesdóttir H, Björnsson H, Pálsson F et al. (2015) Variations of southeast vatnajökull ice cap (Iceland) 1650–1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum. *Geografiska Annaler A – Physical Geography* 97: 237–264.
- Hawkings JR, Wadham JL, Tranter M et al. (2014) Ice sheets as a significant source of highly reactive nanoparticulate iron to the oceans. *Nature Communications* 5: 3929.
- Hayward C (2012) High spatial resolution electron probe micro-analysis of tephra and melt inclusions without beam-induced chemical modification. *The Holocene* 22: 119–125.
- Hernández A, Martín-Puertas C, Moffa-Sánchez P et al. (2020) Modes of climate variability: Synthesis and review of proxy-based reconstructions through the holocene. *Earth-Science Reviews* 209: 103286.
- Hooper J and Marx S (2018) A global doubling of dust emissions during the anthropocene? *Global and Planetary Change* 169: 70–91.
- Humphries MS, Benitez-Nelson CR, Bizimis M et al. (2017) An aeolian sediment reconstruction of regional wind intensity and links to larger scale climate variability since the last deglaciation from the east coast of southern Africa. *Global and Planetary Change* 156: 59–67.

- Hunt JB and Hill PG (1993) Tephra geochemistry: A discussion of some persistent analytical problems. *The Holocene* 3: 271–278.
- Ingólfsson Norðdahl H and Schomacker A (2010) Deglaciation and Holocene glacial history of Iceland. In: Schomacker A, Krüger J and Urt K (eds) *The Mýrdalsjökull Ice Cap, Iceland: Glacial Processes, Sediments and Landforms on an active volcano*. Amsterdam: Elsevier, pp.51–68.
- Jackson MG, Oskarsson N, Trønnes RG et al. (2005) Holocene loess deposition in Iceland: Evidence for millennial-scale atmosphere-ocean coupling in the North Atlantic. *Geology* 33: 509–512.
- Jowsey PC (1966) An improved peat sampler. *New Phytologist* 65: 245–248.
- Jung SJ, Davies GR, Ganssen GM et al. (2004) Stepwise holocene aridification in NE Africa deduced from dust-borne radiogenic isotope records. *Earth and Planetary Science Letters* 221: 27–37.
- Kirkbride MP and Dugmore AJ (2001) Timing and significance of mid-holocene glacier advances in northern and central Iceland. *Journal of Quaternary Science* 16: 145–153.
- Kirkbride MP and Dugmore AJ (2006) Responses of mountain ice caps in central Iceland to holocene climate change. *Quaternary Science Reviews* 25: 1692–1707.
- Kylander ME, Martínez-Cortizas A, Bindler R et al. (2016) Potentials and problems of building detailed dust records using peat archives: An example from store Mosse (the “Great Bog”), Sweden. *Geochimica et Cosmochimica Acta* 190: 156–174.
- Lambert F, Delmonte B, Petit JR et al. (2008) Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature* 452: 616–619.
- Larsen DJ, Miller GH, Geirsdóttir Á et al. (2011) A 3000-year varved record of glacier activity and climate change from the proglacial lake hvítárvatn, Iceland. *Quaternary Science Reviews* 30: 2715–2731.
- Larsen DJ, Miller GH, Geirsdóttir Á et al. (2012) Non-linear Holocene climate evolution in the North Atlantic: A high-resolution, multi-proxy record of glacier activity and environmental change from hvítárvatn, central Iceland. *Quaternary Science Reviews* 39: 14–25.
- Lawrence CR and Neff JC (2009) The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition. *Chemical Geology* 267: 46–63.
- Le Roux G, Fagel N, De Vleeschouwer F et al. (2012) Volcano- and climate-driven changes in atmospheric dust sources and fluxes since the Late Glacial in Central Europe. *Geology* 40: 335–338.
- Maher BA, Prospero JM, Mackie D et al. (2010) Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the last glacial maximum. *Earth-Science Reviews* 99: 61–97.
- Mayewski PA (1999) GISP2 Ions: Deep (D) Core. PANGAEA.
- Mayewski PA, Rohling EE, Curt Stager J et al. (2004) Holocene climate variability. *Quaternary Research* 62: 243–255.
- Moroni B, Arnalds O, Dagsson-Waldhauserová P et al. (2018) Mineralogical and chemical records of Icelandic dust sources upon Ny-ålesund (Svalbard Islands). *Earth Science Frontiers* 6: 187.
- Muhs DR (2013) The geologic records of dust in the Quaternary. *Aeolian Research* 9: 3–48.
- Muhs DR, Budahn JR, McGeehin JP et al. (2013) Loess origin, transport, and deposition over the past 10,000 years, Wrangell-St. Elias National Park, Alaska. *Aeolian Research* 11: 85–99.
- Newton AJ (1996) Tephabase: A Tephrochronological Database. *Quaternary Newsletter* 78: 8–13.
- O'Brien SR, Mayewski PA, Meeker LD et al. (1995) Complexity of holocene climate as reconstructed from a Greenland ice core. *Science* 270: 1962–1964.
- Olsen J, Anderson NJ and Knudsen MF (2012) Variability of the North Atlantic oscillation over the past 5200 years. *Nature Geoscience* 5: 808–812.
- Ovadnevaite J, Ceburnis D, Plauskaite-Sukiene K et al. (2009) Volcanic sulphate and arctic dust plumes over the North Atlantic Ocean. *Atmospheric Environment* 43: 4968–4974.
- Patterson WP, Dietrich KA, Holmden C et al. (2010) Two millennia of North Atlantic seasonality and implications for Norse colonies. *Proceedings of the National Academy of Science of the USA* 107: 5306–5310.
- Prospero JM, Bullard JE and Hodgkins R (2012) High-latitude dust over the North Atlantic: Inputs from Icelandic proglacial dust storms. *Science* 335: 1078–1082.
- Pye K (1987) *Aeolian Dust and Dust Deposits*. London: Academic Press.
- Reimer P, Austin WEN, Bard E et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62: 725–775.
- Ryall DB, Derwent RG, Manning AJ et al. (2002) The origin of high particulate concentrations over the United Kingdom, March 2000. *Atmospheric Environment* 36: 1363–1378.
- Schomacker A, Benediktsson ÍÖ, Ingólfsson Ó et al. (2012) Late-Holocene and modern glacier changes in the marginal zone of Sólheimajökull, South Iceland. *Jökull* 62: 111–130.
- Stewart H, Bradwell T, Bullard J et al. (2017) 8000 years of North Atlantic storminess reconstructed from a Scottish peat record: Implications for holocene atmospheric circulation patterns in Western Europe. *Journal of Quaternary Science* 32: 1075–1084.
- Striberger J, Björck S, Holmgren S et al. (2012) The sediments of Lake lögurinn – A unique proxy record of holocene glacial meltwater variability in eastern Iceland. *Quaternary Science Reviews* 38: 76–88.
- Stuiver M and Reimer PJ (1993) Extended 14C data base and revised calib 3.0 14C Age Calibration Program. *Radiocarbon* 35: 215–230.
- Stuut J-BW and Prins MA (2014) The significance of particle size of long-range transported mineral dust. *PAGES Magazine* 22: 70–71.
- Sugden DE, McCulloch RD, Bory AJ-M et al. (2009) Influence of Patagonian glaciers on Antarctic dust deposition during the last glacial period. *Nature Geoscience* 2: 281–285.
- Terry RD and Chilinger GV (1995) Comparison chart for estimating percentage composition. *Journal of Sedimentary Petrography* 25: 229–234.
- Thevenon F, Chiaradia M, Adatte T et al. (2012) Characterization of modern and fossil mineral dust transported to high altitude in the Western alps: Saharan sources and Transport Patterns. *Advances in Meteorology* 2012: 1–14.
- Vanneste H, De Vleeschouwer F, Bertrand S et al. (2016) Elevated dust deposition in Tierra del Fuego (Chile) resulting from Neoglacial Darwin Cordillera glacier fluctuations. *Journal of Quaternary Science* 31: 713–722.
- Varga G, Dagsson-Waldhauserová P, Gresina F et al. (2021) Saharan dust and giant quartz particle transport towards Iceland. *Scientific Reports* 11: 11891.
- Walker S, Thirlwall MF, Strachan RA et al. (2016) Evidence from Rb–Sr mineral ages for multiple orogenic events in the Caledonides of Shetland, Scotland. *Journal of the Geological Society* 173: 489–503.