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Pathways of high-latitude dust in the North Atlantic

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A B S T R A C T

The contribution of mineral dust from high-latitude sources has remained an under-examined feature of the global dust cycle. Dust events originating at high latitudes can provide inputs of aeolian sediment to regions lying well outside the subtropical dust belt. Constraining the seasonal variability and preferential pathways of dust from high-latitude sources is important for understanding the potential impacts that the dust may have on wider environmental systems, such as nearby marine or cryospheric domains. This study quantifies dust pathways from two areas exhibiting different emission dynamics in the north and south of Iceland, which is a prominent Northern Hemisphere dust source. The analysis uses air parcel trajectory modelling, and for the first time for high-latitude sources, explicitly links all trajectory simulations to time-specific (meteorological) observations of suspended dust. This approach maximises the potential for trajectories to represent dust, and illustrates that trajectory climatologies not limited to dust can grossly overestimate the potential for dust transport.

Preferential pathways emerge that demonstrate the role of Iceland in supplying dust to the Northern Atlantic and sub-Arctic oceans. For dust emitted from northern sources, a dominant route exists to the northeast, into the Norwegian, Greenland and Barents Seas, although there is also potential for delivery to the North Atlantic in summer months. From the southern sources, the primary pathway extends into the North Atlantic, with a high density of trajectories extending as far south as 50°N, particularly in spring and summer. Common to both southern and northern sources is a pathway to the west-southwest of Iceland into the Denmark Strait and towards Greenland. For trajectories simulated at ≤500 m, the vertical development of dust plumes from Iceland is limited, likely due to the stable air masses of the region suppressing the potential for vertical motion. Trajectories rarely ascend high enough to reach the central portions of the Greenland Ice Sheet. The overall distribution of trajectories suggests that contributions of Icelandic dust are relatively more important for neighbouring marine environments than the cryosphere.

1. Introduction

Recent research has cast light on the sources and potential impacts of dust that originates from the global high-latitudes (Bullard et al., 2016). Although considerably smaller in area compared to sub-tropical dust source regions, dust emissions at high-latitudes can be intense (Arnalds, 2010; Bullard, 2013). Many high-latitude, cold climate environments are characterised by winds which regularly exceed the threshold for aeolian entrainment, as well as surfaces with large volumes of fine sediment and little vegetation cover (Bullard, 2013). When combined, these factors promote dust emission into the atmosphere. The main high-latitude dust source regions, defined as ≥50°N and ≥40°S, are Alaska, Canada, Greenland, Iceland, Antarctica, New Zealand and Patagonia (Bullard et al., 2016). Dust storms originating from these areas can cause erosional degradation of soils (Gísladóttir et al., 2010) and are recognised to have a potential impact on air quality (Polissar et al., 1998; Thorsteinsson et al., 2011). Deposition of aeolian transported sediment in such environments can also contribute to local soil development and may have regional and global impacts as material is transferred from the terrestrial to the marine and cryospheric systems (Atkins and Dunbar, 2009; Arnalds et al., 2014). Part of the significance of high-latitude dust sources is that they are found away from the major low latitude global dust belt and are therefore regionally important contributors of aeolian sediment input (Gassó and Stein, 2007; Gassó et al., 2010; Bhattachan et al., 2015; Neff and Bertler, 2015). For example, high-latitude dust storms can input large quantities of sediments to the polar oceans impacting ocean floor sediment accu-

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mulation rates (Chewings et al., 2014). These sediments may also be iron-rich (Schroth et al., 2009) and have the potential to contribute to iron fertilization of the oceans (Nielsdóttir et al., 2009; Arnalds et al., 2014). Crusius et al. (2011) suggested that a single dust storm from the Copper River valley, Alaska contributed 30–200 tons of soluble iron to the iron-limited sub-Arctic north Pacific Ocean.

An increasing body of research has identified seasonal patterns in high-latitude dust emissions at source (recently reviewed by Bullard et al., 2016), but little attention has been paid to the pathways along which the dust is transported. With the notable exception of Patagonia (Gassó and Stein, 2007; Gassó et al., 2010), dust transport pathways from high-latitudes are often omitted from global maps that summarise dust activity and its transport routes (Middleton et al., 1986; Muhs et al., 2014). Commonly based on air trajectory modelling, there has been considerable work into the identification of long term (i.e., multi-year rather than event-based) dust transport patterns from subtropical sources (e.g., McGowan and Clark, 2008; Bhattachan et al., 2012), with far fewer investigations addressing transport from the high-latitudes. High-latitude transport pathways that have been investigated include those from sources in the Dry Valleys of Antarctica (Bhattachan et al., 2015), and from indicative sources in Patagonia and New Zealand (Neff and Bertler, 2015). An important limitation of many contemporary 'dust' transport climatologies that have been produced for both low latitude and high-latitude regions is that they are typically constrained spatially, but not temporally. In other words, trajectories are generated from known dust sources but often for every day of the year rather than being limited only to those seasons or days when dust was actually present in the atmosphere.

The work presented here provides the first long-term, systematic analysis of high-latitude dust pathways that are explicitly associated with dust observations, rather than through a climatology of potential dust transport. Iceland is chosen as a prominent high-latitude dust region, and the aim of this paper is to quantify and understand the impact of source location on dust transport pathways, the variability of pathways as driven by seasonality, and the vertical characteristics of air parcel trajectories associated with dust pathways. Spatially, the study provides insights into which marine areas are most likely to receive aeolian inputs from Iceland, and when, and to what extent there is the potential for the dust to regionally impact the cryosphere.

2. Background

Wind erosion in Iceland is common and the country is recognised as one of Earth's most prominent high-latitude dust sources (Arnalds et al., 2001, 2010; Prospero et al., 2012; Bullard et al., 2016). Surface sediments that are susceptible to aeolian processes cover approximately 20,000 km^2 (Arnalds et al., 2001; Arnalds, 2010), and their location is closely coupled to that of the volcanic-glacial system (Arnalds et al., 2016) (Fig. 1). It has been hypothesised that this area may expand under scenarios of glacial retreat (Cannone et al., 2008) exposing more sediments to potential wind erosion and so increasing the magnitude and frequency of future dust storms (Thorsteinsson et al., 2011; Bullard, 2013).

The most significant dust source regions include north of Vatnajökull (Dagsson-Waldhauserova et al., 2013, 2014) and the southern coast (Thorsteinsson et al., 2011; Prospero et al., 2012), where there are contrasting seasonal patterns of dust emission. In the north, persistent snow cover often restricts dust storms to only the summer months. In the south, dust emissions occur year round, but are less common in summer due to lighter winds and are closely coupled to seasonally-variable sediment supply from

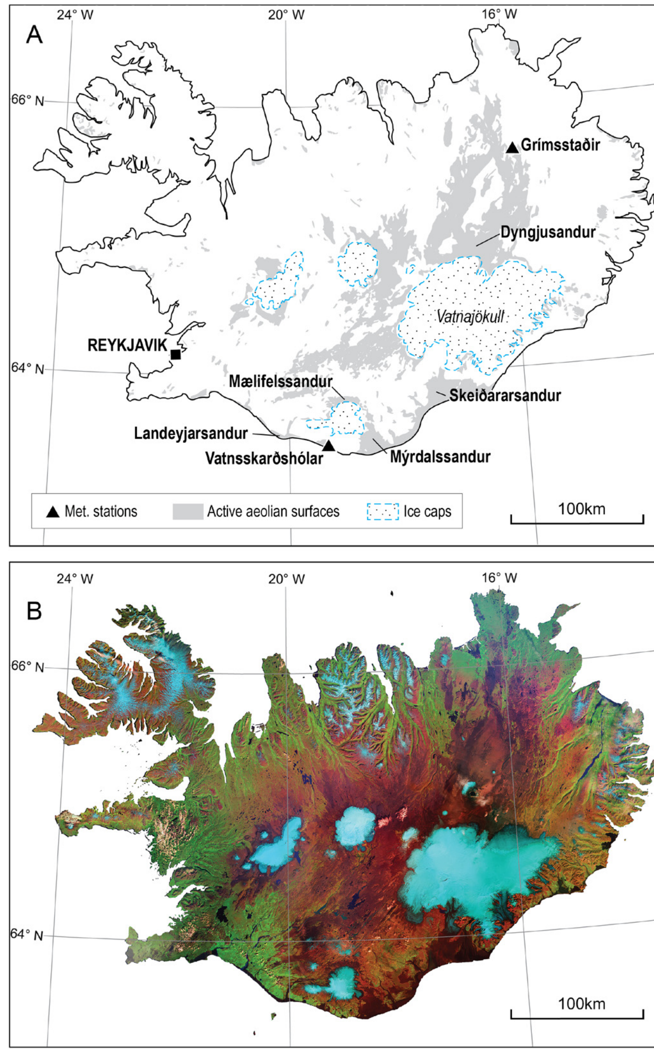

Fig. 1. A) Regional map with key locations for the study. Area of active aeolian surfaces is based on the two highest wind erosion severity land classification categories from Arnalds et al. (2016). B) Landsat Thematic Mapper mosaic of Iceland showing land surfaces. Data from the USGS Tri-Decadal Global Landsat Orthorectified Overview.

the glacio-fluvial system (Old et al., 2005; Prospero et al., 2012; Dagsson-Waldhauserova et al., 2014; Bullard et al., 2016). This system distributes fine sediments across glacial outwash floodplains known locally as sandar. Glacial outburst floods of high magnitude and low frequency (known as jökullhaups) can episodically deliver large amounts of sediment and have been linked to periods of increased dust storm frequency (Prospero et al., 2012).

For the monitoring of regional dust activity, Iceland has an excellent coverage of meteorological stations. Many of these report long-term averages of wind speed and dust-related weather observation codes. Dagsson-Waldhauserova et al. (2014) calculated that Iceland experiences approximately 34 dust days per year, based on a dust day defined as one station recording at least one dust observation. This figure is significantly increased if dust hazes and/or the re-suspension of volcanic ash are included. The impact of wind erosion in Iceland is significant, with dust storms being responsible for approximately 1/3 of all air quality exceedances (>50 μg/m^3, 1 h average) in the greater Reykjavik area, where over 62% of the total population reside (Thorsteinsson et al., 2011).

There have been few studies of the transport of dust from Iceland despite the fact that the surrounding oceans have been identified as a region where phytoplankton are possibly respon-

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