Pathways of high-latitude dust in the North Atlantic

Matthew C. Baddock[a], Tom Mockford[a], Joanna E. Bullard[a] and Throstur Thorsteinsson[b]

[a]Department of Geography, Loughborough University, Loughborough, UK LE11 3TU

m.c.baddock@lboro.ac.uk; t.mockford@lboro.ac.uk; j.e.bullard@lboro.ac.uk

[b]Environment and Natural Resources & Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavik, Iceland

ThrosturTh@hi.is

Corresponding author:

Matthew Baddock (m.c.baddock@lboro.ac.uk)

Abstract

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 50ºN, 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.

Keywords; Iceland, Greenland, aerosols, Arctic, HYSPLIT

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 accumulation 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 (Nielsdottir 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) (Figure 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).

>>Figure 1<<

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 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 responsive to iron inputs (Nielsdóttir et al., 2009). Arnalds et al. (2014) used a variety of assumptions to estimate dust budgets and deposition rates on land and into oceans to the northeast and south of the island. They estimated that the contribution of dust to the North Atlantic from Icelandic sources might be up to 7% of the quantity supplied to the same location from North African sources. In terms of longer-distance transport, Dagsson-Waldhauserova et al. (2013) have suggested that Icelandic dust may reach Greenland. They highlighted that two periods of elevated dust and one of its relative absence in Greenland Summit ice cores analysed by Donarummo et al. (2002) could be correlated with a 40-year meteorology-based record of dust from northeast Iceland. In finding some particles described as glassy in texture, which they associated with volcanics, Drab et al. (2002) also proposed a potential route for aerosols from Iceland to Greenland. Real-time aerosol mass spectrometry observations of Icelandic dust reaching Ireland have also suggested that Iceland could provide a regional source of aerosol over the North Atlantic (Ovadnevaite et al., 2009). In their recent review article, however, Arnalds et al. (2016) stress that investigations of long range dust transport from Iceland have relied on case studies and are as yet lacking systematic analysis.

3. Methods

Dust transport from Iceland was analysed using forward air parcel modelling 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 computes the position of an air parcel as driven by three-dimensional winds at hourly time steps for a user-determined duration. HYSPLIT, developed by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration, is a widely-used air parcel trajectory model and its developers have recently reviewed the developmental history and use of the model by the atmospheric science community, including examples of its successful application in numerous studies of mineral dust transport (see Stein et al., 2015). While HYSPLIT can be used in a full dispersion mode, this analysis of dust pathways from Iceland was based on frequency and distribution of HYSPLIT derived trajectories.

HYSPLIT has previously been used to investigate possible pathways from dust sources over multi-year time periods. Where dust transport is the focus, researchers have ensured that trajectories are started from known dust sources, but if no account is taken of when these sources are active then there is a risk that air parcel pathways that do not contain dust are included in the analysis. Long term climatologies of all trajectories from emission sources therefore only demonstrate *potential* pathways of dust (e.g., McGowan & Clark, 2008; Bhattachan et al., 2012; Bhattachan et al., 2015). In the current study, we produce a long term transport climatology that is more representative of actual dust transport by only analysing air trajectories related to days and times of dust observation made near Icelandic dust sources. The dust records of two Icelandic meteorological stations at Grímsstaðir and Vatnsskarðshólar were used (Figure 1). These stations were selected for two reasons. First, they have been identified as key indicator stations of dust activity in the north and south of Iceland respectively (e.g., Dagsson-Waldhauserova et al., 2013; 2014) (Figure 1). Second, a long term record exists over a period common to both locations, allowing all dust observations between 1992-2012 to be considered. According to the multi-decadal analysis of Icelandic dust observations by Dagsson-Waldhauserova et al. (2013), this 20 year period provides an adequate dataset of trajectories from which to derive principal dust pathways (Table 1).

>>Table 1<<

To compare the results of a full climatology with one restricted to dust observations, firstly, HYSPLIT input control files were batch generated for every day of the study period at a start time of 1200 UTC (7305 trajectories for each site). For analysis of dust-associated pathways (i.e. those constrained to days of dust observation), trajectories were also generated for only those days when a dust-related SYNOP code 06 ('widespread dust in suspension away from the station') were reported. In the Icelandic aeolian setting, some of these dust events involve the entrainment and re-suspension of volcanic material that had previously been deposited at the surface (Thorsteinsson et al., 2012; Bullard et al., 2016). For these runs, trajectories were originated at the station site and at the specific time that the dust code was reported. This time was the first dust observation if several dust events occurred at several times on a given day. By running forward trajectories for known dust days, from locations and times where dust was observed, our analysis is based on trajectories that are explicitly associated with known instances of dust suspension.

An important consideration in using dust records from meteorological stations is that the presence of a dust weather code report indicates dust at the reporting station, not that the location is necessarily the source of the dust (O'Loingsigh et al., 2010). In this study however, Grímsstaðir and Vatnsskarðshólar are stations closely associated with Icelandic dust source areas as identified by Arnalds (2010), Arnalds et al. (2014) and Dagsson-Waldhauserova et al. (2013) (Figure 1), so these stations can be taken to represent the activity of source areas. The specific relationships between the location of these two stations and the principal sources of Icelandic dust emission are discussed later.

The meteorological input to drive the HYSPLIT simulations was the monthly NCEP/NCAR global reanalysis product, a commonly used dataset with 2.5° spatial resolution and described in detail by Kalnay et al. (1996) (see also Harris et al., 2005; Stein et al., 2015). Based on input data, HYSPLIT generates a modelled position for an air parcel and therefore trajectory points on an hourly basis. The method for calculation of vertical motion employed in the model was a 3D vertical wind field derived from the reanalysis data. In producing their climatology of potential dust transport in Australia, McGowan and Clark (2008) ran trajectories for 8 days, arguing that fine dust can remain suspended for that length of time. In our study we compute trajectories for a three day (72 hour) period. While the maximum possible extent of dust transport from Iceland might not be covered over this timescale (Neff and Bertler, 2015), HYSPLIT trajectory accuracy decreases at longer periods (Stohl, 1998), and a shorter timescale increases confidence that the simulated trajectories will represent dust in transport, because (dry and wet) depositional fall-out also increases with time. For this trajectory analysis, a decay parameter for dust in suspension was not considered. The fate of suspended dust at a relatively low level height was evaluated by one set of HYSPLIT simulations run with air parcel start height at 100 m above ground level (a.g.l.), and also at greater altitude by another group of trajectories starting at 500 m. The start height for HYSPLIT trajectories varies considerably throughout the literature, and is typically determined by specifics of the research and study location. Neff and Bertler (2015) for instance recently presented a major climatology of southern hemisphere dust source trajectory analysis based on a 100 m start height for HYSPLIT, while McGowan and Clark (2008) used a 500 m start height for their study of Australian transport pathways. We select two relatively low heights because the focus of this study is not an estimation of the longest potential range for dust transport from Iceland, but to maximise certainty that modelled trajectories do represent the transport of dust entrained from a particular source area. In a unique meteorological experiment overflight which also captured an Icelandic dust event, Blechschmidt et al. (2012) reported the visibility reduction due to dust was more pronounced at observations made below 700 m. These observations provide some support that our simulation run heights of 100 m and 500 m are well within the dust layer.

Summary analysis of the trajectory points from the HYSPLIT model output, including their organisation into seasonal periods, was performed in ArcGIS. Maps of trajectory frequency density are displayed in two ways. The trajectory model produces hourly iteration points in space, and where analysis permitted points to be joined, trajectories were treated as a complete line, so frequency was expressed as the percentage of lines passing through 1 x 1º cells on a regular latitude-longitude grid. Using the same grid, the variation of trajectories by altitude was quantified as the percentage of points occurring at different heights.

To assist in the interpretation of near-surface wind fields, dust transport, and the key relationship between emission source areas and the meteorological observation stations, indicative wind roses were generated for Grímsstaðir and Vatnsskarðshólar. These roses were based on mean windspeed from three hourly measurements using data from the Icelandic Meteorological Service for every day of the 20 year study period.

4. Results

Figure 2 presents a comparison of trajectory frequency distribution between a full climatology, run on a daily basis regardless of whether or not dust was observed at the source, and the trajectory distribution restricted to dust-associated days only. The full climatologies for the two stations appear as approximately concentric rings of trajectory density decreasing away from Iceland, with slight biases in the peak densities extending north and south from Grímsstaðir and Vatnsskarðshólar respectively (Figure 2A and 2C).

>>Figure 2<<

The distribution of the trajectories associated explicitly with dust observations at each station (Figure 2B and D) reveals an appreciably different pattern compared with the full climatologies. The spatial extent of trajectory density is considerably reduced, and reveals potential preferential pathways for dust transport. From Grímsstaðir, a zone of relatively high trajectory densities can be seen to extend to the north and northeast of Iceland, reaching just beyond 70ºN into the Norwegian and Greenland Seas. In total, over a quarter (28.1%) of trajectory points occurred north of 70ºN. A less prominent but distinct pathway from Grímsstaðir is also detected to the west of Iceland, toward the Greenland coast and into the Denmark Strait. From the southern station of Vatnsskarðshólar, two broad corridors of more dense trajectories are apparent into the North Atlantic, including a predominantly southerly one extending to around 54ºN, and another more southwesterly pathway, the latter somewhat similar to that seen for Grímsstaðir. Only 2.4% of Vatnsskarðshólar trajectory points were found north of 70°N within the three day period of leaving Iceland. With the same simulation start height (100m) for both the full and dust-associated trajectories, one clear feature is the greatly reduced density of trajectories over Greenland for the dust-associated air parcels.

To examine the potential for variability in pathway characteristics with altitude, the dust-associated trajectories were compared for two different starting heights of 100 m and 500 m a.g.l. (Figure 3). Simulations from Grímsstaðir starting at 100 m showed that the vast majority of trajectories do not rise vertically and remain under 500 m (Figure 3A, 3C). For this low level start height, the density maps indicate that both the northerly and westerly pathways for dust from northern Iceland are best developed by trajectories occurring <100 m; westerly trajectories reach the coast of Greenland (Figure 3A, 3C).

>>Figure 3<<

Results from simulations started at both 100 m and 500 m show that trajectories must exceed 500 m altitude to pass over Greenland, and are more likely to do so if the trajectories originate at 500 m (Figure 3E, 3F). For those dust-associated trajectories initiated at 500 m and reaching >1500 m, just over a quarter cross Greenland (Figure 3H), although this represents only 2.5% of the total trajectory points started at 500 m. Relatively few of the trajectories starting at 500 m descend to <100 m (Figure 3B).

The spatial characteristics of dust-related air parcels with height originating at Grímsstaðir contrast with those from Vatnsskarðshólar (Figure 4). At the 100 m start height, the southerly pathway from Vatnsskarðshólar extends to 55ºN for trajectory points <100 m (Figure 4A), while both the southerly and southwesterly pathways are best defined by air parcels between 100 and 500 m (Figure 4C). The simulations begun at 500 m from Vatnsskarðshólar indicate that the southerly Icelandic dust pathway is most active for lower level trajectories between 100-500 m (Figure 4D). The passage of dust to the southwest is more associated with trajectories at higher altitudes (500-1500 m) (Figure 4F). Very few air parcels climb to above 1500 m from Vatnsskarðshólar (Figure 4G, 4H).

>>Figure 4<<

Another important potential driver of dust pathways is seasonality (e.g., McGowan and Clark, 2008). The seasonal spatial distribution of trajectory lines computed from 100 m a.g.l. when dust was observed at Grímsstaðir is shown in Figure 5. A clear feature of the winter (December-February) period for the Grímsstaðir station is that dust activity is infrequent, with very few dust events recorded in the 20 year study period (1.5% of total). Spring (March-

May) has more activity, with the most common routes for dust at this time being to the northeast. The majority of trajectories (58.6%) from the north of Iceland occur in summer (June-August). The likelihood of dust being transported to the south over the North Atlantic is greatest in these JJA months, and overall trajectory dispersal is also most widespread in this period, including the greatest potential to reach Greenland. In the autumn period (September-November), fewer trajectories head to the south and the northerly pathway becomes more dominant.

>>Figure 5<<

For dust observed at Vatnsskarðshólar, winter again emerges as the least active period, but for this site, the percentage of trajectories occurring in winter is around six times greater than at Grímsstaðir (9.4%) (Figure 6). In MAM 35.4% of trajectories occur, and in JJA 33.4%, indicating a similar degree of activity for both of these seasons. In MAM however, the pathway to the southwest of Iceland appears to be more prevalent, whereas the frequency of dust transport to the south or southeast increases during JJA. The southerly dust route is also dominant in autumn.

>>Figure 6<<

5. Discussion

The first output of this study was a comparison between all possible air parcel trajectories and those trajectories constrained to occasions of dust observation at meteorological stations in north and south Iceland (Figure 2). From the 20 year dataset, the modelled transport patterns indicate there are considerable differences between a gross assessment based on all pathways versus those that are specifically dust-associated. An important note in this case is that such differences may be especially pronounced in the case of high-latitude dust source regions. In high-latitude environments, acute temporal variability of sediment availability has been identified as a critical factor in controlling dust activity (e.g., Nickling, 1978; Bullard et al., 2016). The clearest example of this is the dust pathway behaviour in winter from the northern site of Grímsstaðir. Here, emission and therefore transport is effectively shut down by winter snow cover in northern Iceland (Figure 5) (Dagsson-Waldhauserova et al., 2013). The trajectory distribution from Grímsstaðir derived from daily-resolved simulations that include the winter period will therefore be heavily biased by trajectories unlikely to be dust laden (Figure 2A). Furthermore, in a daily climatology not discerned by dust, trajectories on days where windspeed is below the threshold for entrainment will also be included. It is by linking trajectories to the presence of dust that the preferential pathways for dust transport from Iceland emerge (Figure 2B and 2D).

The long term analysis of trajectories associated with observed dust days from Iceland reveals particular patterns, but before any inferences can be made about the pathways from specific source areas, the spatial relationship between each dust observing station and the major emission sources needs to be considered. For example, Dagsson-Waldhauserova et al. (2013) have demonstrated that the major source area for dust events recorded at Grímsstaðir is the sandy glacial floodplain of Dyngjusandur which lies to the south of Grímsstaðir (Figure 1). The relative position of the source and the meteorological station means that episodes of above-threshold winds from the north that are capable of entraining dust from Dyngjusandur and transporting it to the south are unlikely to be detected at Grímsstaðir. As a result of this spatial relationship, there is a likelihood that computation of trajectories for dust observed at Grímsstaðir will not represent all instances that the Dyngjusandur source was emitting. Analysis of the long term wind characteristics at Grímsstaðir however reveals that the majority of winds likely to be competent for dust entrainment (>8 ms^{-1}) (Gisladottir et al., 2005) are south-southwesterly (Figure 7). This indicates that Grímsstaðir is located downwind of the major source area for the majority of potentially dust raising occasions, and therefore represents an appropriate monitoring station from which to make inferences about the fate of dust from the Dyngjusandur source.

<<Figure 7>>

Seasonal wind roses for Vatnsskarðshólar reveal the dominance of strong surface winds from an easterly direction (Figure 8). This wind regime and the upwind location of Mýrdalssandur and Skeiðararsandur as source surfaces to the east and north-east of Vatnsskarðshólar suggests that this station is likely to record the majority of local dust events (Figure 1). Westerly winds are rare for Iceland (Einarsson, 1984), but a component of this at Vatnsskarðshólar during summertime effectively links dust observations in JJA to possible emission from the coastal Landeyjarsandur source (Figure 1, Figure 8). The differences in the wind roses between the two stations partly demonstrate the importance of local, topographic influence on near-surface airflow at

Vatnsskarðshólar and reduced topographic influence on airflow at the more open location of Grímsstaðir (Dagsson-Waldhauserova et al., 2013).

<<Figure 8>>

With an understanding of the relationship between observed dust days at Grímsstaðir and Vatnsskarðshólar and the specific Icelandic dust sources that these stations may be taken to reflect, the drivers of the large-scale transport pathways can be interpreted. The key dust transport pathways from Iceland relate chiefly to major wind systems associated with the large scale synoptic circulation for the North Atlantic and sub-Arctic region. Wind patterns over Iceland are strongly controlled by the presence of the Icelandic Low, a persistent low pressure feature lying to the southwest of the country which establishes the most common flow over Iceland as from between northeast and south (Einarsson, 1984; Arnalds et al., 2016). In this region, individual cyclonic systems frequently occur as disturbances from the polar front, and movement of these systems west to east in the vicinity of Iceland can cause large surface pressure variations, which have been studied in detail by Serreze et al. (1997) and Nawri (2015). The typical high wind speed events resulting from this can account for the average dust pathway patterns seen from both Grímsstaðir and Vatnsskarðshólar.

Figures 2B and 2D reveal that a broad pathway to the west-southwest of Iceland toward Greenland and into the Denmark Strait is common to both Grímsstaðir and Vatnsskarðshólar. This route for dust is attributable to the influence of easterly winds associated with the dominant track for cyclonic passage that exists to the south of Iceland (Olafsson et al., 2007; Thorsteinsson et al., 2011; Arnalds et al., 2016). Activation of this pathway occurs when the pressure fields during cyclonic events are sufficient to generate dust-raising winds and when the surface is susceptible to erosion. Thus, the dust pathway to the west of Iceland is most apparent during the summer for Grímsstaðir and spring for Vatnsskarðshólar (Figures 5B and 6C), with the later occurrence at the more northerly Grímsstaðir where snow cover is more prolonged (Dagsson-Waldhauserova et al., 2013). The contribution of this pathway to the west-southwest, well defined in the trajectory analysis, was not considered by Arnalds et al. (2014) in their first attempt to estimate the loading of Icelandic dust to surrounding marine systems.

From Grímsstaðir, another preferential route for dust can be seen heading to the north-northeast (Figure 2B, Figure 5). This path is associated with strong southerly (SW-S-SE) winds that are typical in the northern part of Iceland, driven by winds at the western or leading edge of anticlockwise cyclonic systems as they pass west to east below Iceland (Einarsson, 1984; Dagsson-Waldhauserova et al., 2013; Arnalds et al., 2014). Throughout the year, the most common threshold-exceeding surface winds are from the south (Figure 7), and while the strongest winds are most frequent in winter, snow cover makes this a time of reduced dust emission in northern Iceland (Figure 5A) (Dagsson-Waldhauserova et al., 2013). While Dagsson-Waldhauserova et al. (2013) report that springtime dust events in northeastern Iceland are commonly associated with near surface winds from the southeast, the trajectory analysis from a 100 m start height reveals the dominant long distance transport pathway from Grímsstaðir is to the northeast in MAM (Figure 5B). This indicates that while surface wind conditions at source drive entrainment activity, they are not necessarily the best indicator of long range transport patterns.

For Vatnsskarðshólar, the majority of the strongest surface winds occur from the east (Figure 8), establishing a route for dust from southern sandar sources that has been noted to affect Reykjavík (Thorsteinsson et al., 2011). In the current study, 6.25% of all dust-associated trajectories run forward from Vatnsskarðshólar were found to track over or within 25 km of the municipality area of Reykjavik. The occurrence of relatively infrequent westerly flows (most common in summer, Figure 8) is related to cyclones taking a less usual, more northerly course between Greenland and Iceland (Arnalds et al., 2016). While most near-surface winds occur from the east, air parcel trajectories originating at 100 m reveal that a well-defined path for dust from Vatnsskarðshólar advects southward, indicating a distinct route into the mid-Atlantic (Figure 2D, Figure 6). This pathway has been illustrated in MODIS imagery of dust storms by Prospero et al. (2012) and Arnalds et al. (2014) in their approach of estimating dust deposition rates into marine regions surrounding Iceland. Arnalds et al. (2014) discuss dry northeasterly winds as the main driver of dust transport from the southern coastal sandurs to the south, which are often brought about by conditions of high pressure over Greenland, and deep cyclonic systems east of Iceland (Einarsson, 1984; Blechschmidt et al., 2012). The southerly pathway from Vatnsskarðshólar to the North Atlantic is evident all year round, but is most active in JJA, and is the dominant pathway in SON when it is more active than the broad west-southwesterly path to Greenland (Figure 6). The prominence of this pathway was in fact demonstrated in real time aerosol trace monitoring by Ovadnevaite et al. (2009) who linked aerosol sampling conducted on the west coast of Ireland, to an individual long distance (1300 km) Icelandic summertime dust event.

Trajectory analysis suggests that dust originating from both northern and southern sources has the potential to impact the North Atlantic Ocean (Figure 5C, 6). For Vatnsskarðshólar, the occurrence and extent of trajectories into the North Atlantic is roughly equal between spring and summer (Figure 6B, 6C), but contributions from Grímsstaðir primarily occur in the summer. In contrast, dust contributions to the Greenland Sea and Norwegian Sea is almost exclusively from sources in the north of Iceland (Figure 5). This is likely to be because northerly winds above threshold on the south coast are rare (Figure 8) and because winds to the south are promoted by both orographic and glacial influences immediately to the north of the southern coastal sources (Einarsson, 1984) (Figure 1).

While the cyclonic systems that bring about strong northerly and southerly flows are frontal and often precipitation bearing, Arnalds et al. (2016) comment that the altitudinal barriers imposed by highlands and glaciated parts of Iceland can create leeward rain shadow regions that are significant for dust-raising potential. The same study demonstrates that precipitation in northern Iceland is rare during southerly winds, and rare in southern Iceland for northerly winds. These rain shadow conditions on the opposite sides of barriers help explain the transport route to the south from Vatnsskarðshólar (Figure 2D) under northerly winds, and the northern pathway from Grímsstaðir (Figure 2B) during southerly winds.

Analysis of the trajectories by height shows the relative lack of vertical development for air parcels from both Grímsstaðir and Vatnsskarðshólar (Figure 3 and 4). This may be attributable to the dominance of stable atmospheric conditions throughout the region which prevents trajectories from achieving higher altitudes within the three day simulation (Harris et al., 2005). Arnalds et al. (2014) in their calculation of the Icelandic dust sediment budget also commented that dust storms in the region are typically associated with conditions of stable, stratified flow. They point out that air masses only have a short duration of advection over land from the central Icelandic dust source area of Dyngjusandur before reaching the coast, and therefore receive relatively limited warming from the surface, even in summer months. Any thermal influence is even more limited for dust emitted from sandar on the southern coast (Figures 1 and 4). This is in contrast to the dynamics of desert dust sources in lower latitudes where convection from strong surface heating encourages rising air parcels and transport of dust at well developed height, for example >3 km for the Saharan dust pathway over the central Atlantic (Liu et al., 2007).

While analysis of trajectory height is dependent on the reliability of the vertical motion in the HYSPLIT model, some confidence in the findings here stems from the sensitivity analysis of trajectory modelling conducted by Harris et al. (2005). Their study compared the performance of HYSPLIT with NCAR/NCEP reanalysis input data versus other input meteorology, vertical transport methods and different models for trajectories in the Canadian Arctic, thereby considering a similar atmospheric environment to the present study. While not seeking to assess the absolute accuracy of trajectory heights, Harris et al. (2006) found that mean trajectory altitude after 96 hours from NCAR/NCEP reanalysis was within 50 m of that from alternative ERA-40 input data. Furthermore, their comparison of an isentropic method to estimate vertical motion found that mean trajectory height was 600 m less than a kinematic calculation of vertical motion. This suggests that in using the latter method for the current Icelandic study, our approach is not under-estimating trajectory height, strengthening the suggestion that trajectories and dust transport remains relatively low level.

The systematic trajectory analysis presented here reveals that most air parcels starting from 500 m or less from Iceland have little potential to cross onto the Greenland Ice Sheet (GrIS). The fact that trajectories are seen to skirt the edge of the GrIS indicates that three day simulations provide adequate time for air parcels to reach the Greenland coast, but that the lack of vertical motion restricts parcels from ascending onto the ice (e.g., Figure 3A, 3D). The steep terrain at the edge of Greenland exerts an influence that prevents low-level trajectories cross onto land, and the trajectory point density in Figure 3 reveals that air parcels starting at 500 m from Grímsstaðir represent the most likely route for dust to Greenland, but only 5.3% of total trajectory points are found to reach over Greenland. For trajectories run from Grímsstaðir at the extreme start height of 2000 m (not shown here), the proportion marginally increases to 6.5% indicating that start height does not dramatically influence the potential for Icelandic dust to reach the GrIS. A number of regions have been identified as contributing dust to the GrIS including both distal sources in North Africa and Asia, and high-latitude dust sources (Kahl et al. 1997; VanCuren et al., 2012). Groot-Zwaaftink et al. (2016) modelled dust deposition in the Arctic and concluded that the relative importance of different sources depends on the altitude of the surface on which the dust is being deposited. For example, over Greenland in total 67% of dust is of high-latitude origin, but over the highest parts of the GrIS this contribution drops to <15% because dust transported from Africa and Asia becomes relatively more important. Dust reaching Greenland from Asian and Saharan sources travels thousands of kilometres and will have been thoroughly mixed to high altitudes (e.g., Saharan Air Layer) (Liu et al., 2008; Engelstaedter et al., 2009) enabling the far-travelled dust to penetrate over the GrIS. A mechanism for this high altitude dust being detectable by ground level sampling is the periodic lessening of the semi-permanent temperature inversion over the GrIS at springtime polar sunrise (Mosher et al., 1993).

Of the high-latitude dust deposited over the GrIS, a proportion is likely to have originated in Iceland and travelled along the pathways identified in this study. This is also suggested by Drab et al. (2002) who found the presence of glassy particles up to 5 μm diameter in aerosol sampling at Summit, Greenland. They inferred a relatively nearby volcanic source, possibly Iceland, based on the large particle size and composition. While comprising a minority of the material detected (cf. clays), it was suggested these glassy particles might represent volcanic material re-suspended from the surface (e.g., Thorsteinsson et al., 2012), thus supporting a route from ground level in Iceland to the Greenland Interior. Arrival of Icelandic dust to Greenland has also been suggested by Dagsson-Waldhauserova et al. (2013) based on speculative matching between their meteorological time series of dust observation and the GISP2 ice core dust record presented by Donarummo et al. (2002).

While the trajectory analysis does not take into account the potential for vertical mixing as a possible means for dust to ingress further onto the GrIS, and it is difficult to verify the accuracy of vertical motion in the HYSPLIT model (Harris et al., 2005), overall, the modelled pathways and regional atmospheric stability suggests that under contemporary wind conditions, dust from Iceland might have a relatively limited potential for cryospheric interactions over GrIS. In terms of cryospheric processes, Icelandic dust sources may be important for local ice caps and glaciers but this has yet to be explored in detail (Casey and Kääb, 2012; Bullard et al., 2016).

6. Conclusion

This work presents the first long term assessment, constrained by actual dust observations, of dust transport from a high-latitude dust region. Air parcel trajectories were examined for a 20 year period from two source areas exhibiting different emission dynamics due to their location in the north and south of Iceland. By comparing the trajectories of a coarse climatology versus specifically dust-associated trajectories, this study highlights the imperative of basing trajectory analysis for dust transport studies on occasions when dust emission occurred. Studies that use daily-run climatologies at best represent potential pathways and may suggest considerably different transport patterns to those when the analysis is restricted to days when dust activity was observed.

A notable aspect of the current study is the fact it was facilitated by the robust sources of meteorological data available for Iceland. Datasets indicating the presence and absence of dust are critical to the validity of the approach used, and yet, such meteorological records are sparse in remote high-latitude areas. Exploring the availability of datasets in other high-latitudes is key to a wider, global assessment of dust transport from these regions. Weather observations from meteorological stations offer a useful indicator for the presence of dust, but as this paper has discussed, station position in relation to source areas, and the influence of prevailing wind direction, means meteorological stations can only be considered proxies for sources of emission. The spatial disconnect between meteorological sites and source areas, and the variability of wind fields, means there is always a potential for emission to be missed when analysis is led by meteorological observations.

In terms of the Icelandic dust system, the analysis has defined preferential pathways that demonstrate the role of Iceland in distributing dust to the Northern Atlantic and sub-arctic oceans. Apparent for dust emitted from both the southern coastal and northeast sandur (glacial outwash floodplain) sources is a pathway of dust to the west-southwest of Iceland into the Denmark Strait and towards Greenland. From northern sources, a route also exists to the northeast, into the Norwegian, Greenland and Barents Seas, although there is also potential for delivery to the North Atlantic Ocean in summer months. From the southern sources, the dominant pathway extends into the North Atlantic, with elevated trajectory frequency extending as far as 50ºN, particularly in spring and summer. For simulations run from <500 m, where concentrations of dust are greater in the lower atmospheric boundary layer, trajectories reveal that the vertical development of dust plumes from Iceland is limited. This is likely due to the stable air masses of the region suppressing the potential for vertical motion of air parcels and therefore transport of mineral aerosol. Such an influence on airflow has implications for the likelihood of dust reaching the major cryospheric system of the Greenland Ice Sheet, with trajectories being unlikely to ascend high enough to reach the central ice sheet. From an Earth systems view, the overall distribution of trajectories indicates that contributions of Icelandic dust are relatively more important for neighbouring marine environments.

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Table 1: Details of study meteorological stations and 1992-2012 dust observation datasets

	Location	Altitude (m)	Number of dust days	Average dust days per year
Grímsstaðir	16.121ºW 65.642ºN	384	202	10.1
Vatnsskarðshólar	19.183ºW 63.424ºN	20	160	8

Figure Captions

Figure 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.

Figure 2: Trajectory line density (% of trajectories per 1°x1º cell) for 72 hour simulations run at a 100 m start height from Grímsstaðir for all days 1992-2012 (A), and dust observation days only (B), from Vatnsskarðshólar for all days 1992-2012 (C), and dust observation days only (D). See Figure 1 for trajectory start points.

Figure 3: Trajectory point density (% of points per 1ºx1º cell) at different altitudes for 72 hour simulations started at 100 m height (left hand column) and 500 m height (right hand column), originating from Grímsstaðir for days of observed dust 1992-2012. See Figure 1 for trajectory start points.

Figure 4: Trajectory point density (% of points per 1°x1º cell) at different altitudes for 72 hour simulations started at 100 m height (left hand column) and 500 m height (right hand column), originating from Vatnsskarðshólar for days of observed dust 1992-2012. See Figure 1 for trajectory start points.

Figure 5: Seasonal variation in trajectory line density (% of trajectories per 1°x1º cell) for simulations started at 100 m height originating from Grímsstaðir on days of observed dust 1992-2012. See Figure 1 for trajectory start points.

Figure 6: Seasonal variation in trajectory line density (% of trajectories per 1°x1º cell) for simulations started at 100 m height originating from

Vatnsskarðshólar on days of observed dust 1992-2012. See Figure 1 for trajectory start points.

Figure 7: Directional frequency of winds (>8 m s^{-1}) representing near-surface airflow at Grímsstaðir, as derived from mean three-hourly wind speeds for the whole study period 1992-2012.

Figure 8: Directional frequency of winds (>8 m s^{-1}) representing near-surface airflow at Vatnsskarðshólar, as derived from mean three-hourly wind speeds for the whole study period 1992-2012.

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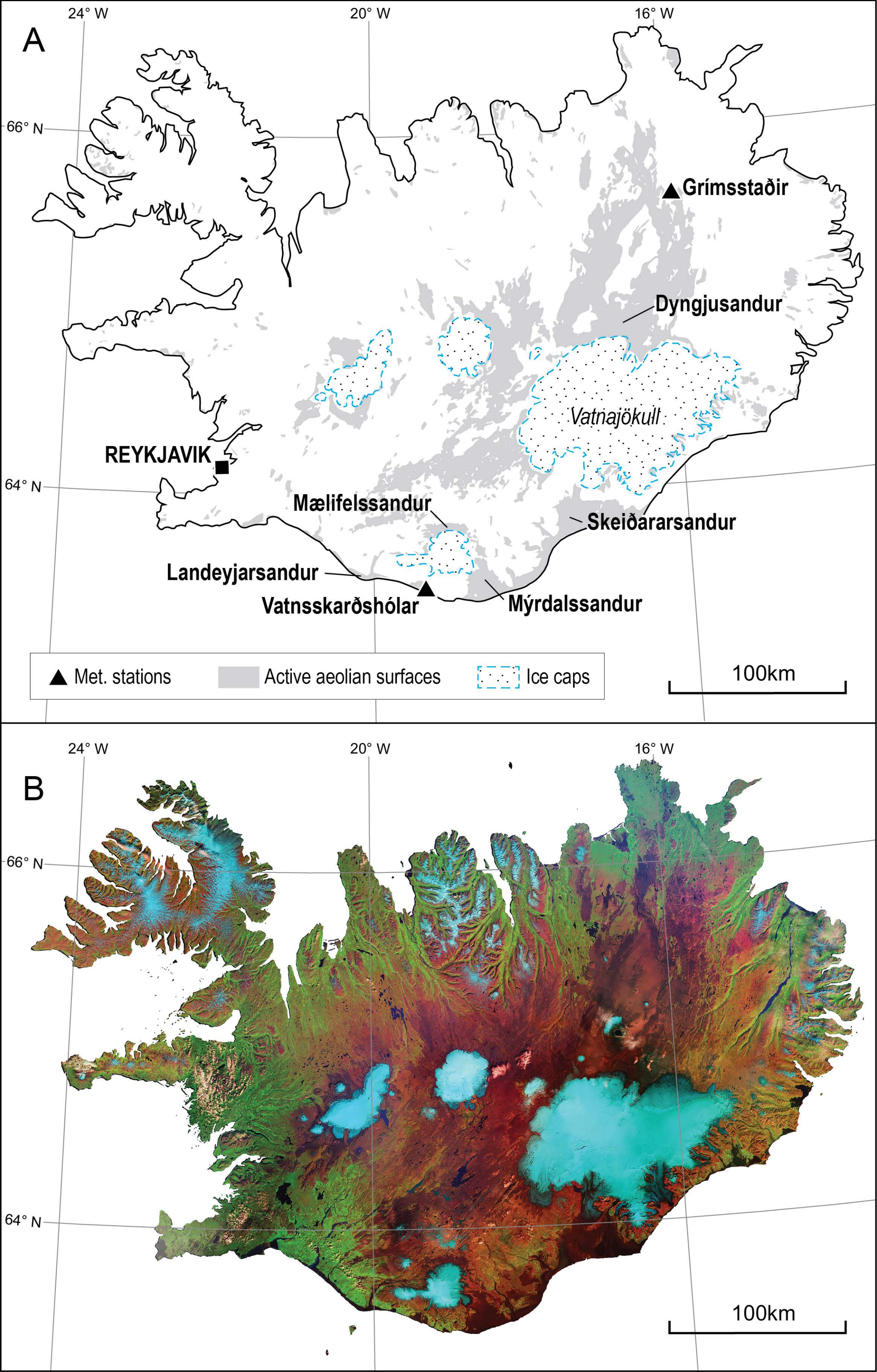
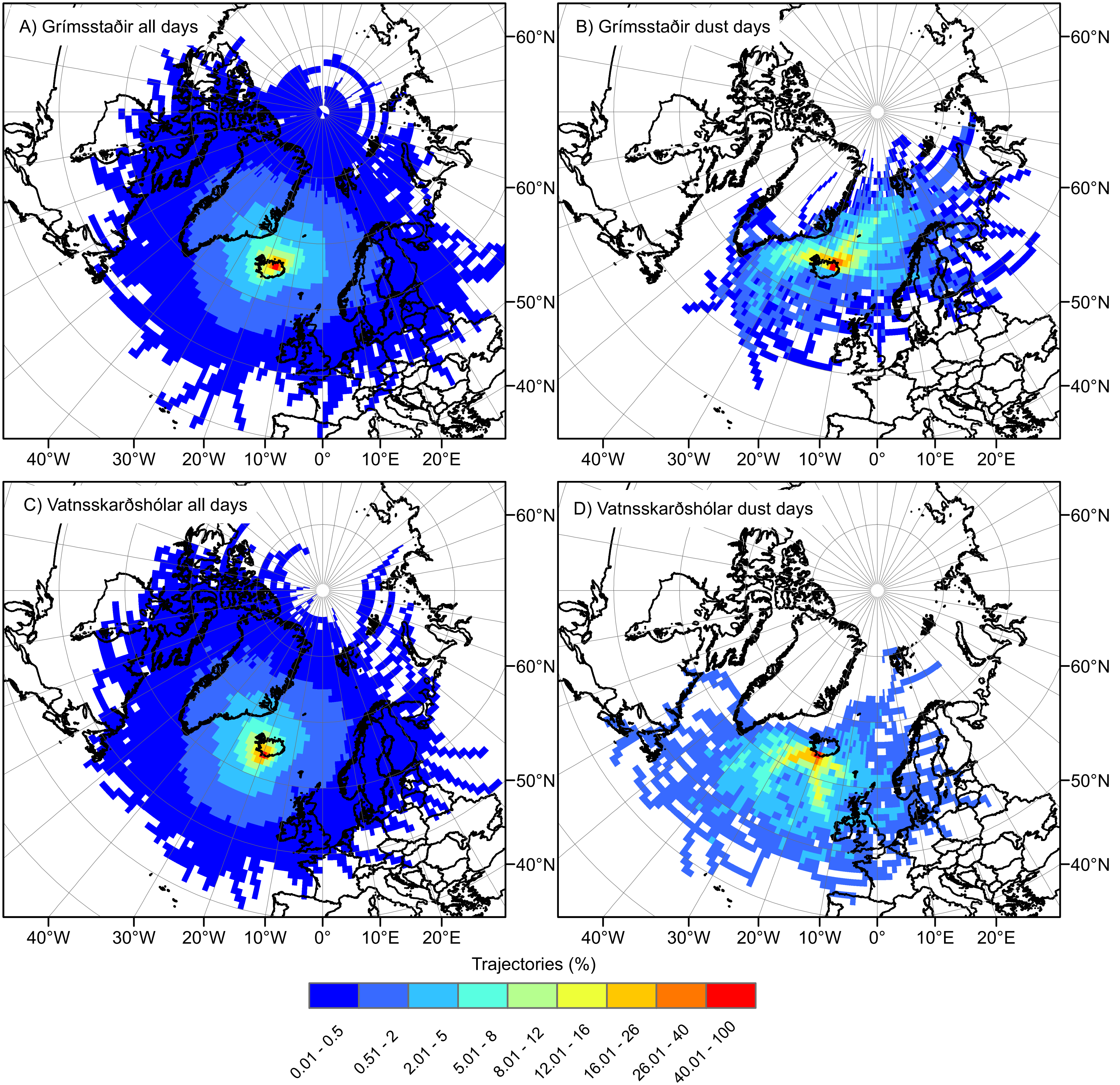
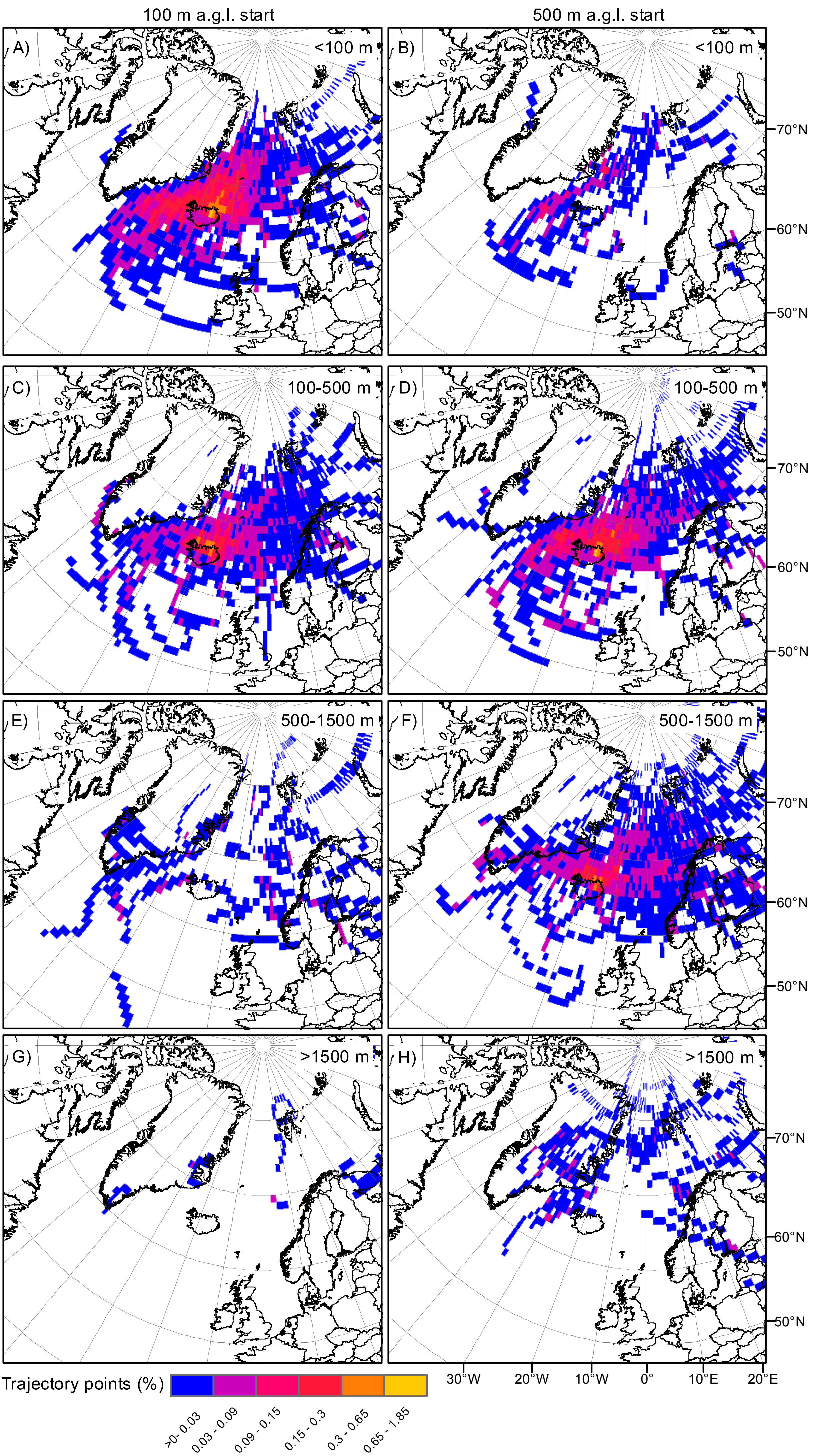
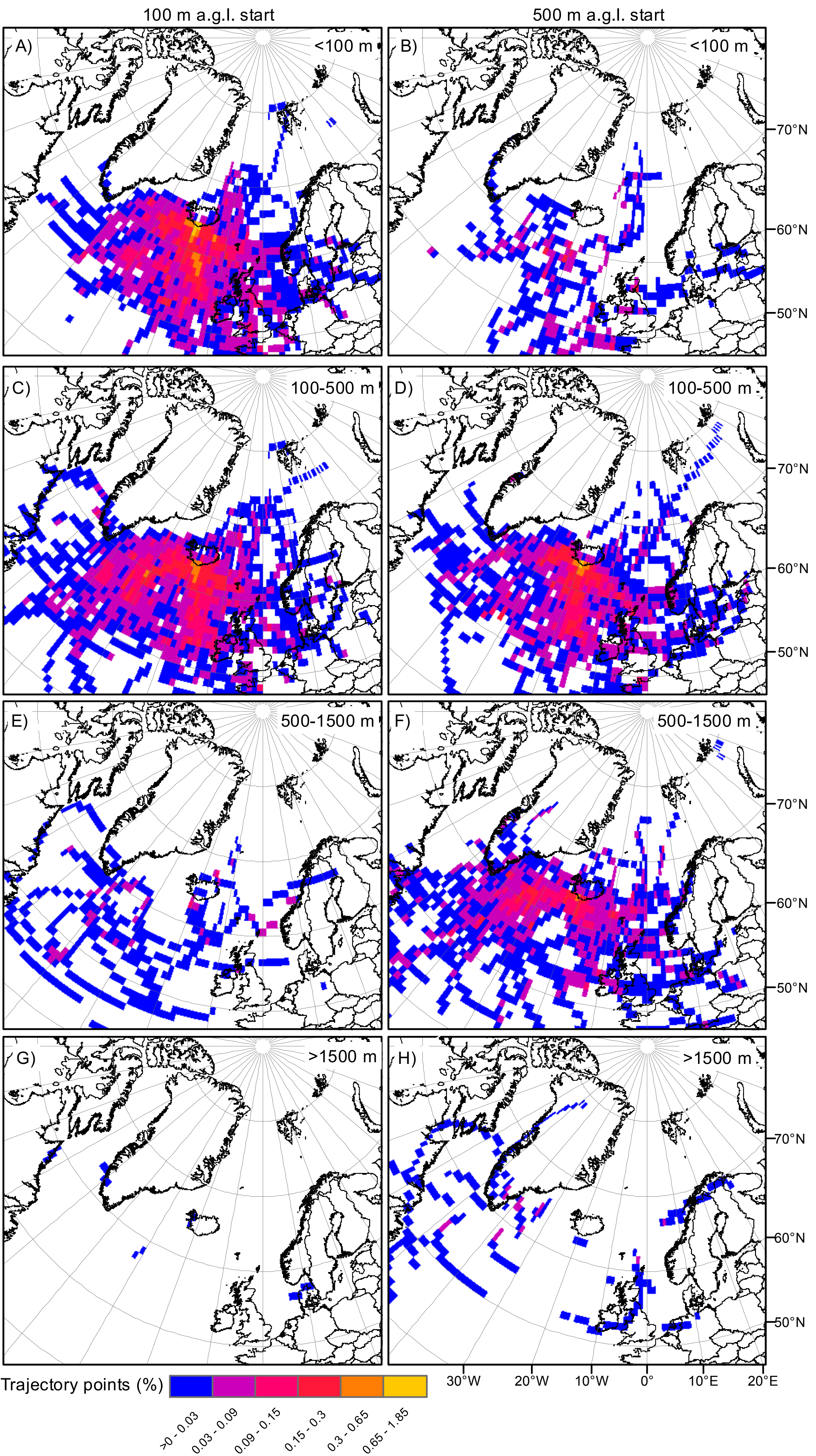
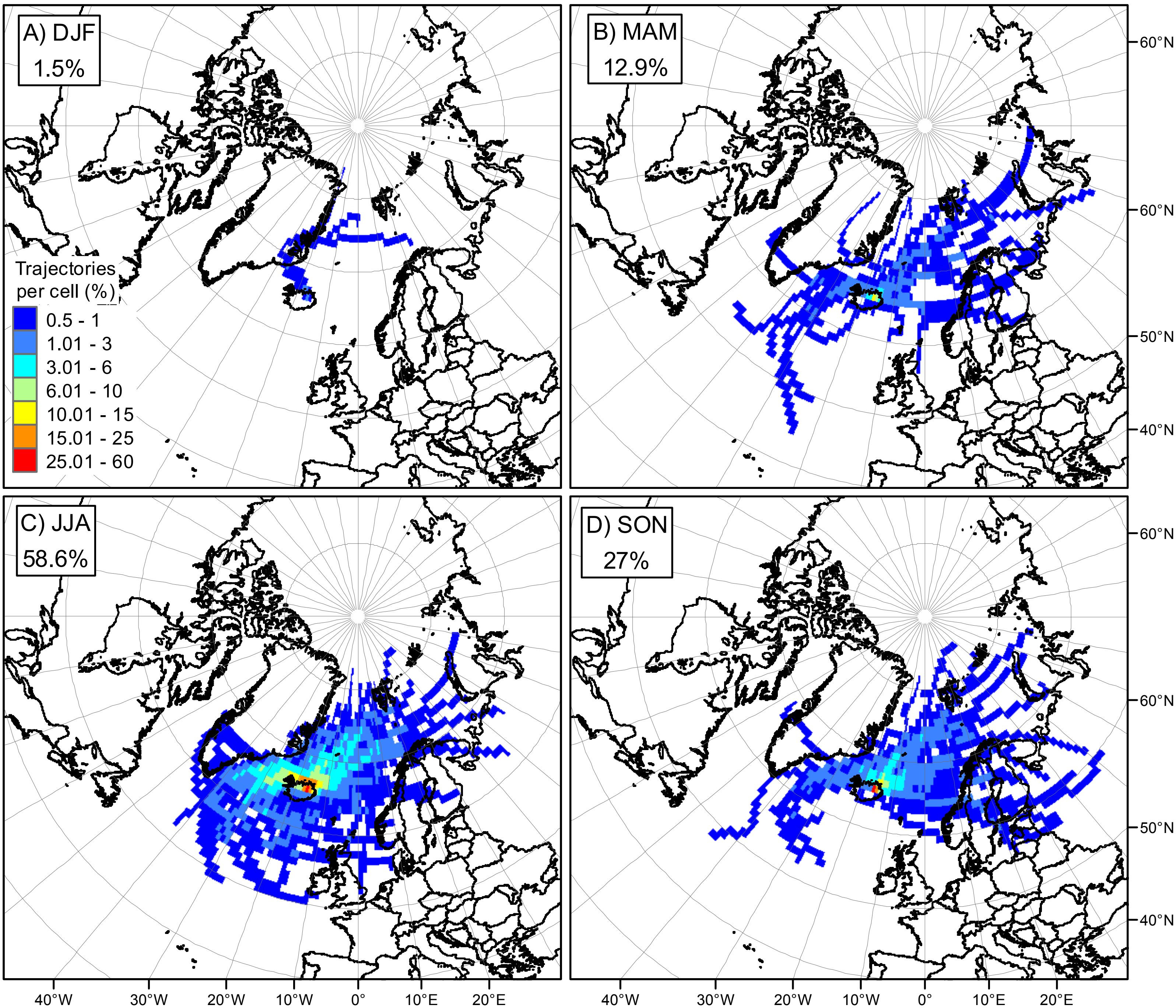

A
24° W
20° W
16° W
66° N
64° N
Grímsstaðir
Dyngjusandur
Vatnajökull
REYKJAVIK
Mælifelssandur
Skeiðararsandur
Landeyjarsandur
Vatnsskarðshólar
Mýrdalssandur
Met. stations
Active aeolian surfaces
Ice caps
100km
B
24° W
20° W
16° W
66° N
64° N
100km


A) Grímsstaðir all days
B) Grímsstaðir dust days
C) Vatnsskarðshólar all days
D) Vatnsskarðshólar dust days
60°N
50°N
40°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
Trajectories (%)
0.01 - 0.5
0.51 - 2
2.01 - 5
5.01 - 8
8.01 - 12
12.01 - 16
16.01 - 26
26.01 - 40
40.01 - 100

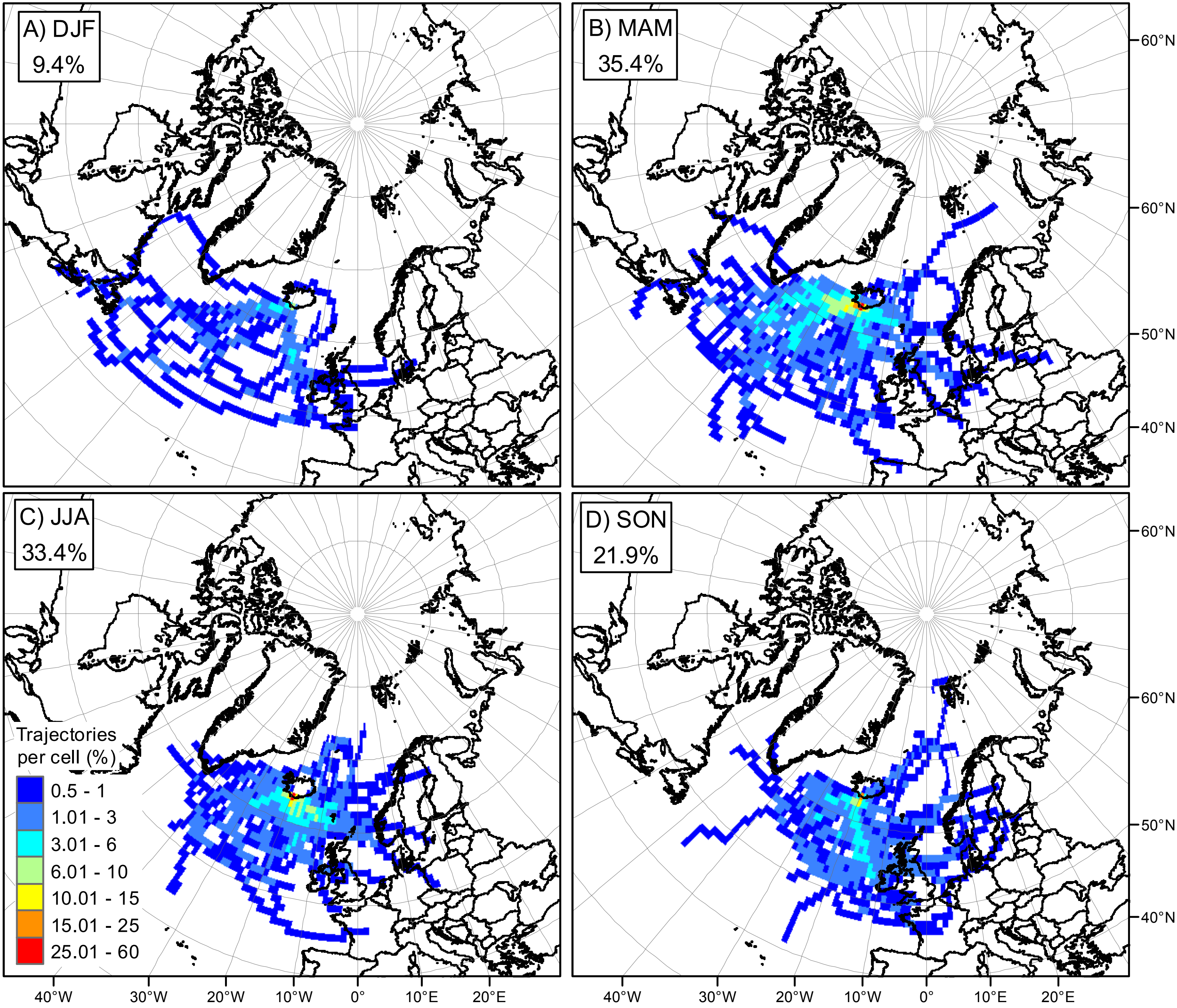


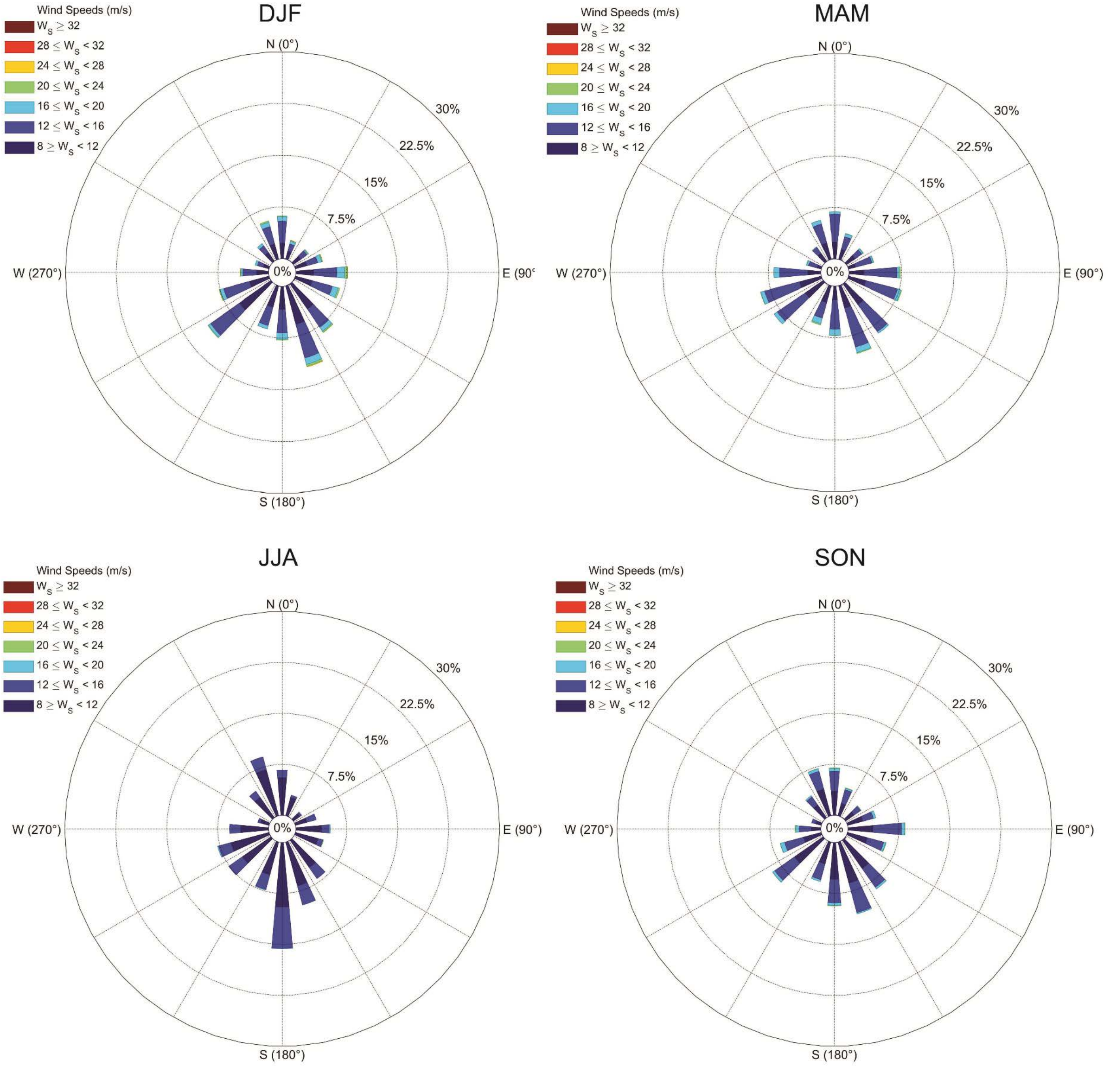
100 m a.g.l. start
500 m a.g.l. start
A)
<100 m
B)
<100 m
C)
100-500 m
D)
100-500 m
E)
500-1500 m
F)
500-1500 m
G)
>1500 m
H)
>1500 m
70°N
60°N
50°N
30°W
20°W
10°W
0°
10°E
20°E
Trajectory points (%)
>0- 0.03
0.03 - 0.09
0.09 - 0.15
0.15 - 0.3
0.3 - 0.65
0.65 - 1.85

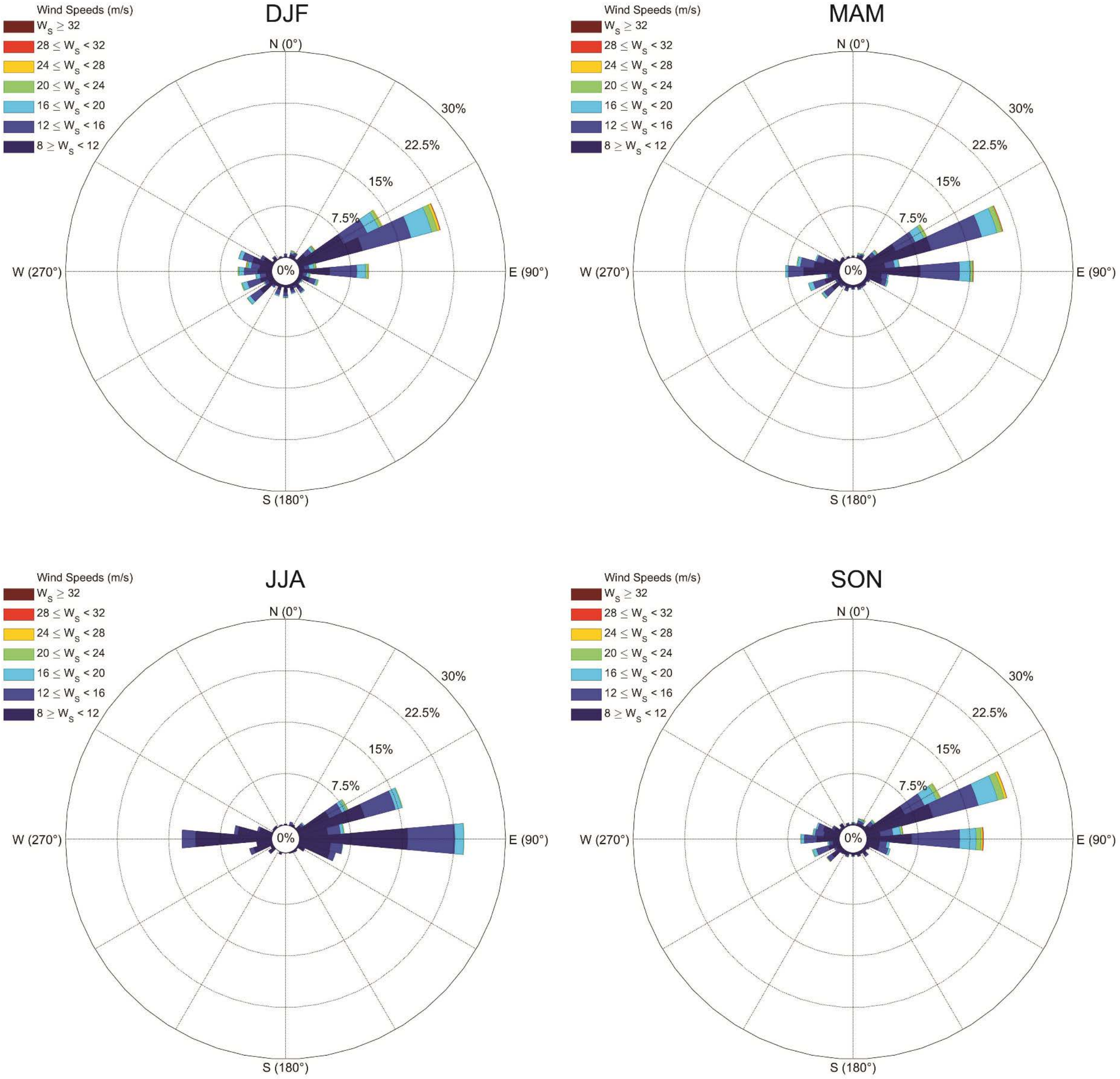

100 m a.g.l. start
500 m a.g.l. start
A)
<100 m
B)
<100 m
C)
100-500 m
D)
100-500 m
E)
500-1500 m
F)
500-1500 m
G)
>1500 m
H)
>1500 m
70°N
60°N
50°N
30°W
20°W
10°W
0°
10°E
20°E
Trajectory points (%)
>0 - 0.03
0.03 - 0.09
0.09 - 0.15
0.15 - 0.3
0.3 - 0.65
0.65 - 1.85



A) DJF
1.5%
B) MAM
12.9%
C) JJA
58.6%
D) SON
27%
Trajectories per cell (%)
0.5 - 1
1.01 - 3
3.01 - 6
6.01 - 10
10.01 - 15
15.01 - 25
25.01 - 60
60°N
60°N
50°N
40°N
60°N
60°N
50°N
40°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
40°W
30°W
20°W
10°W
0°
10°E
20°E


A) DJF
9.4%
B) MAM
35.4%
C) JJA
33.4%
D) SON
21.9%
Trajectories per cell (%)
0.5 - 1
1.01 - 3
3.01 - 6
6.01 - 10
10.01 - 15
15.01 - 25
25.01 - 60
60°N
50°N
40°N
40°W
30°W
20°W
10°W
0°
10°E
20°E


DJF
MAM
JJA
SON
Wind Speeds (m/s)
$W_S \geq 32$
$28 \leq W_S < 32$
$24 \leq W_S < 28$
$20 \leq W_S < 24$
$16 \leq W_S < 20$
$12 \leq W_S < 16$
$8 \geq W_S < 12$
N (0°)
E (90°)
S (180°)
W (270°)
0%
7.5%
15%
22.5%
30%


Wind Speeds (m/s)
W_S ≥ 32
28 ≤ W_S < 32
24 ≤ W_S < 28
20 ≤ W_S < 24
16 ≤ W_S < 20
12 ≤ W_S < 16
8 ≥ W_S < 12
DJF
N (0°)
30%
22.5%
15%
7.5%
W (270°)
0%
E (90°)
S (180°)
Wind Speeds (m/s)
W_S ≥ 32
28 ≤ W_S < 32
24 ≤ W_S < 28
20 ≤ W_S < 24
16 ≤ W_S < 20
12 ≤ W_S < 16
8 ≥ W_S < 12
MAM
N (0°)
30%
22.5%
15%
7.5%
W (270°)
0%
E (90°)
S (180°)
Wind Speeds (m/s)
W_S ≥ 32
28 ≤ W_S < 32
24 ≤ W_S < 28
20 ≤ W_S < 24
16 ≤ W_S < 20
12 ≤ W_S < 16
8 ≥ W_S < 12
JJA
N (0°)
30%
22.5%
15%
7.5%
W (270°)
0%
E (90°)
S (180°)
Wind Speeds (m/s)
W_S ≥ 32
28 ≤ W_S < 32
24 ≤ W_S < 28
20 ≤ W_S < 24
16 ≤ W_S < 20
12 ≤ W_S < 16
8 ≥ W_S < 12
SON
N (0°)
30%
22.5%
15%
7.5%
W (270°)
0%
E (90°)
S (180°)