



# Temporal and spatial variability of Icelandic dust emission and atmospheric transport

Christine D. Groot Zwaaftink<sup>1</sup>, Ólafur Arnalds<sup>2</sup>, Pavla Dagsson-Waldhauserova<sup>2,3,4</sup>, Sabine Eckhardt<sup>1</sup>, Joseph M. Prospero<sup>5</sup>, Andreas Stohl<sup>1</sup>

5 <sup>1</sup> NILU Norwegian Institute for Air Research, Kjeller, Norway

<sup>2</sup> Agricultural University of Iceland, Hvanneyri, Iceland

<sup>3</sup> Faculty of Physical Sciences, University of Iceland, Reykjavik, Iceland

<sup>4</sup> Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic

<sup>5</sup> Department of Atmospheric Sciences & Rosenstiel School of Marine and Atmospheric Science, University of Miami

10 *Correspondence to:* Christine Groot Zwaaftink (cgz@nilu.no)

**Abstract.** Icelandic dust sources are known to be highly active, yet there exist few model simulations of Icelandic dust that could be used to assess its impacts on the environment. We here present estimates of dust emission and transport in Iceland over 27 years (1990-2016) based on FLEXDUST & FLEXPART simulations and meteorological re-analysis data. Simulations for the year 2012 based on high-resolution operational meteorological analyses are used for model evaluation based on PM<sub>2.5</sub> and PM<sub>10</sub> observations in Iceland. For stations in Reykjavik, we find that the spring period is well predicted by the model, while dust events in late fall and early winter are overpredicted. Six years of dust concentrations observed at Stórhöfði (Heimaey) show that the model predicts concentrations in the same order of magnitude as observations and timing of modelled and observed dust peaks agrees well. Annual dust emission amounts to  $4.3 \pm 0.8$  Tg during the 27 years of simulation. Fifty percent of all dust from Iceland is on average emitted in just 25 days of the year, demonstrating the importance of a few strong events for annual total dust emissions. Annual dust emission as well as transport patterns correlate only weakly to the North Atlantic Oscillation. Deposition amounts in remote regions (Svalbard and Greenland) vary from year to year. Only limited dust amounts reach the upper Greenland Ice Sheet, but much dust is deposited on Icelandic glaciers and can impact melt rates there. Approximately 34% of the annual dust emission is deposited in Iceland itself. Most dust (58%) however, is deposited in the ocean and may strongly influence marine ecosystems.

## 25 1 Introduction

Mineral dust is known to influence the radiation budgets of the atmosphere and cryosphere, ecosystems and human health. Even though fragile climate and ecosystems at high latitudes can be impacted, high-latitude dust sources have received rather little attention to date. Dust sources at high latitudes are often associated with glaciers. Glaciers produce fine material and, especially in floods, much dust is deposited in glacio-fluvial plains. Dust mobilization at high latitudes is strongly influenced by wind speeds, which are often quite strong in the presence of katabatic winds, sediment supply or dust availability, snow cover, freezing processes, and vegetation (e.g. Bullard et al., 2016). The combination of these factors often leads to a strong



seasonality in dust emission or dust storm frequency at high latitudes. High-latitude dust sources are for instance found at the coast in southern Alaska (Crusius et al., 2011), West-Greenland (Bullard and Austin, 2011) and Iceland (Arnalds et al., 2016). Model simulations indicated that 0.3% of global dust emission may originate from Iceland (Groot Zwaaftink et al., 2016) and it is known that dust storms frequently occur there (Dagsson-Waldhauserova et al., 2014). Icelandic dust storms impact air quality in Reykjavik (e.g. Thorsteinsson et al., 2011), glacier melt rates (e.g. Wittmann et al., 2017) and deposit iron-rich material in the North Atlantic (e.g. Prospero et al., 2012) where it can fertilize the ocean (e.g. Achterberg et al., 2013). Estimates of dust emission and transport amounts in Iceland have been based on storm frequency and visibility observations (Arnalds et al., 2014). Transport pathways from two main dust source regions have been studied (Baddock et al., 2017) and qualitatively describe regions that may be affected. Model simulations of dust emission in Iceland however, are lacking. These could greatly improve dust emission estimates and help not only to identify regions possibly affected by Icelandic dust, but also to allow for quantitative results in regions where no measurement data are available. We here aim to model and discuss such long-term dust emission with an adapted version of FLEXDUST (Groot Zwaaftink et al., 2016) and study dust transport with FLEXPART (Stohl et al., 2005). The complex interaction with the glacial system is currently not represented, but we use a highly detailed surface type map of Iceland to identify dust sources. We present a brief model evaluation, discuss interannual variability of dust emission and transport, and estimate dust deposition to the ocean, Icelandic glaciers, Greenland and Svalbard.

## 2. Methods and data

### 2.1 Model description

#### FLEXDUST

A model for estimates of dust emission, FLEXDUST, has been introduced by Groot Zwaaftink et al. (2016). This model estimates dust emission as a function of friction velocity and threshold friction velocity, based on the approach introduced by Marticorena and Bergametti (1995), and originally accounts for snow cover, topography (Ginoux et al., 2001) and soil moisture (Fécan et al., 1999). Modelled dust emission rates have a cubic dependency on friction velocity. The model is forced by analysis data of the European Centre for Medium-range Weather Forecasts (ECMWF). For dust emission in Iceland, the model is combined with a surface type map presented by Arnalds (2015). As we have a highly detailed surface type map, we here do not include large scale topography effects to identify sediment regions in Iceland as was done by Groot Zwaaftink et al. (2016) to estimate global dust emissions. The estimation of the threshold friction velocity for mobilization also differs from the standard approach in FLEXDUST. We use observations from Arnalds et al. (2001) and their description of erosion levels to determine the threshold friction velocity (see Table 1). Arnalds et al. (2016) give an overview of erosion classes for each surface type. So called dust hot spots, described by Arnalds et al. (2016), were also included in our simulations. These were assigned a lower friction velocity (see Table 1) and slightly larger soil fraction (+3%). A map of the Icelandic soil fraction in FLEXDUST is shown in Figure 1. In total, about  $16.7 \cdot 10^3$  km<sup>2</sup> of the sandy deserts are categorised as active aeolian sources.



Notice the close proximity of Icelandic dust sources to glaciers on Iceland, which is important for dust deposition on glacier surfaces.

As we here mainly deal with sediments, we assume that precipitation is a more adequate indicator of decreased mobilization than soil moisture, and soil moisture does not affect threshold friction velocities. This was confirmed in a test case where soil moisture did affect threshold friction velocity and the resulting modelled dust concentrations were an order of magnitude lower than observed particulate matter concentrations at several stations in Iceland (also see section 2.3). Thus, in our current simulations, no dust emission occurs if precipitation exceeds 1 mm per hour and soil moisture has no influence on dust mobilization. We assume a closed snow cover will inhibit dust emission if snow depth, retrieved from ECMWF analysis fields, exceeds 0.1 m water equivalent. In case dust sources near glaciers were falsely categorized as glaciers in the ECMWF data due to low resolution, snow depth at a reference point in interior Iceland was used. We further assume that the Westfjords area (west of 20°W and north of 65.2 °N) does not emit dust as it has limited extent of dust sources (Arnalds, 2015). Furthermore, long-term dust frequency showed occurrence of about one dust day in five years in the Westfjords and this dust could also have been transported to the Westfjords from the central deserts (Dagsson-Waldhauserova et al., 2014). Emitted dust is assumed to have a size distribution according to Kok (2011). Particles are split in 10 bins of different sizes; the first 5 bins are for particles up to 5 micrometre diameter, the remaining 5 bins extend up to 20 micrometres.

## FLEXPART

FLEXPART 10.0 is used to calculate atmospheric transport of emitted dust from Iceland, as was previously also done for Saharan dust (Sodemann et al., 2015) and globally emitted dust (Groot Zwaafink et al., 2016). FLEXPART is a Lagrangian particle dispersion model (Stohl et al, 1998; 2005) driven by external meteorological fields. The model calculates trajectories of a multitude of particles to describe transport and diffusion of tracers in the atmosphere. In FLEXPART, simulated dust particles are influenced by gravitational settling, dry deposition and in-cloud and below-cloud scavenging (Grythe et al., 2016). We used the default scavenging coefficients for dust and assume that particles are spherical. In this study we use ECMWF operational analysis and ERA Interim reanalysis data to force FLEXPART.

## 2.2 Simulation setup

We did both high-resolution simulations for the year 2012 and a series of relatively low resolution simulations for the years 1990 to 2016. For computational reasons the longer time series were split in annual simulations, each with an additional spin-up period of one month. The high-resolution simulation in 2012 was based on hourly, 0.2° operational ECMWF analysis fields. Dust emission was calculated on a 0.01 degree resolution at hourly intervals. Emitted particles were gathered in hourly releases at 0.05 degrees resolution. The high-resolution simulation for 2012 included about 40 million particles. The long-term simulations were based on 3-hourly ERA Interim reanalysis fields at 1° spatial resolution. For these simulations, dust emissions in FLEXPART were calculated at 0.02 degrees resolution on a 3-hourly basis and then gathered in 6-hourly releases at 0.5 degrees. Each annual simulation included on average roughly 10 million particles.



## 2.3 Observations

For model evaluation, measurements of concentration of particulate matter (PM) smaller than 10 micrometre (PM<sub>10</sub>) and smaller than 2.5 micrometre (PM<sub>2.5</sub>) are used together with dust concentrations. PM data are available at stations in Reykjavik (Grensasvegur and FHG), Hvaleyrarholt and Raufarfell, operated by the Environment Agency of Iceland. Locations are shown in Figure 1. The stations at Grensasvegur and FHG are equipped with a Thermo EMS Andersen FH 62 I-R instrument, the station at Hvaleyrarholt with Thermo SHARP model 5030 and the station at Raufarfell with Thermo 5014i. Observations were done hourly and averaged to daily values. PM measurements used here include PM<sub>10</sub> and PM<sub>2.5</sub>, if available at the respective station, in the year 2012. In this year no volcanic eruptions occurred that could strongly influence PM measurements. Nevertheless, PM includes many particle types other than mineral dust (e.g. sea salt, anthropogenic emissions).

Dust concentrations were measured on Heimaey at a lighthouse at Stórhöfði (63°23.885'N 20°17.299'W, 118 m a.s.l.) on a daily basis with a high-volume filter aerosol sampler which collects total suspended particulates. Longer exposure times occurred occasionally due to bad weather and strong winds that precluded filter changing (Prospero et al., 2012). The observations were set up to study dust from remote sources, thus sampling was only done for wind directions south to west. Measurements used here cover the period 8 February 1997 to 3 January 2003 and were averaged to weekly values.

## 3. Results and discussion

### 3.1 Evaluation

Model evaluation is limited due to a lack of data. Especially in north-east Iceland, where large dust sources are present, dust data are scarce. For earlier simulations using FLEXDUST and FLEXPART Wittmann et al. (2017) showed a comparison of dust deposited on Vatnajökull and observed deposition in snow samples, concluding that modelled spatial distribution of dust deposition on this scale was similar to observations and dust deposition amounts were of the right order of magnitude. Satellite data are mostly valuable during dust events and require cloudless conditions and adequate overpass time of the satellite. Although visual inspection of MODIS images has confirmed particular dust events that will be discussed (such as in May 2012), they do not provide quantitative data and we do not include these. Here, we restrict model evaluation to measurements of PM and dust concentrations in south-west Iceland.

#### 3.1.1 PM concentrations

Concentrations of particulate matter in Iceland included different types of aerosols. Especially for stations near roads like Grensasvegur, concentrations are influenced by traffic. Dust storms are a recurring cause of episodes with elevated PM<sub>10</sub> concentrations (>50 µg m<sup>-3</sup>) in Reykjavik (Thorsteinsson et al., 2011). The station Raufarfell, however, is located in the vicinity of dust sources and other influences are relatively small. Observed PM<sub>10</sub> values (Figure 2) are frequently lower than PM<sub>2.5</sub> values (Figure 3) in our data, even though this is, by definition, not possible. Since both quantities were measured with different



instruments this can occur due to measurement errors in either of (or both of) the instruments. We have marked periods where PM<sub>2.5</sub> values exceed PM<sub>10</sub> values with grey shading in Figures 2 and 3. During these days, observations either underestimate PM<sub>10</sub> values or overestimate PM<sub>2.5</sub> values, of which the latter is most likely given operational problems with these sensors. In 2012 (Figure 2), several larger dust events occurred between May and November. There is a good agreement between the observations and the model at Raufarfell and most events are also represented in our FLEXPART simulation. In late September events are modelled at Raufarfell that were not visible in the observations, causing an overestimate of the number of days with concentration levels exceeding 50 µg m<sup>-3</sup> (Table 2). With the exception of the strongest dust event at the end of the measurement series, modelled concentrations are somewhat overestimating PM<sub>10</sub> concentrations. This could also be related to topography, with the station placed in a mountain wind shade that might not be captured in the model. Nevertheless, the mean simulated concentration (28 µg m<sup>-3</sup>) is close to the mean observed PM<sub>10</sub> concentration (21 µg m<sup>-3</sup>, Table 2), with almost identical standard deviations, indicating that dust variability is well captured.

All other measurement stations are located near or in Reykjavik and are at larger distance from dust sources, and shorter distance to the ocean. This means that a) the measurements are less influenced by mineral dust and more strongly by other components (e.g. sea salt, road dust, pollution) and b) we expect larger discrepancies between model and observations as besides dust emission atmospheric transport and removal processes become increasingly important. At Hvaleyrarholt larger dust events, such as in May, are nicely captured by the model. Differences between modelled and observed concentrations may of course also be influenced by the uncertainties in size estimates both in the observations and simulations, and in particular the effective size cut-off in the measurements. Especially during fall and early winter, PM<sub>10</sub> concentrations are overestimated by the model. The results for PM<sub>2.5</sub> (Figure 3) are very similar at this station. At the remaining stations in Reykjavik we clearly see increased background PM values (likely due to traffic). The model obviously underestimates these background values as only mineral dust is included in our simulations. Dust events are best recognized in peaks that occur simultaneously at FHG and Grensasvegur. Two distinct dust storms in May are indeed nicely represented by the model. The larger difference between measured and modelled PM<sub>2.5</sub> than PM<sub>10</sub> values may indicate that particle size distribution should be shifted, although it could also be due to a larger influence of anthropogenic aerosols on PM<sub>2.5</sub> values. As for Hvaleyrarholt, we find that the estimated number of dust storms reaching Reykjavik in fall and early winter is rather too large in the model. Even though the dust storms at Raufarfell appeared nicely captured in this period (as far as measurements were available), it could be that other dust sources causing dust storms in Reykjavik are less well represented in our model. The highly dynamic nature of glacio-fluvial dust sources (e.g. Bullard, 2013) is not captured in our model and for instance depletion of specific dust sources during summer can explain the difference between model and observations.

High PM<sub>10</sub> concentrations in Reykjavik are a cause of concern. A health limit is set at 50 µg m<sup>-3</sup> and this should not be exceeded on more than 7 days per year (Thorsteinsson et al., 2011). In observations discussed by Thorsteinsson et al. (2011) this limit was reached up to 29 days per year. In 2012 the daily value of 50 µg m<sup>-3</sup> was exceeded on 7 days according to the measurements at Grensasvegur and on 16 days in the simulation (including only days with observations), as also shown in Table 2. The number of days with PM<sub>10</sub> exceeding 50 µg m<sup>-3</sup> also appear overestimated at the other three stations (Table 2).



Median values of modelled dust concentrations in Table 2 are generally lower than median values of observed PM10 concentrations, as expected since PM10 also includes other aerosol types.

### 3.1.2 Stórhöfði - Heimaey dust concentration

The weather station at Stórhöfði is one of the weather stations in Iceland with the largest number of reported dust days in long-term records (Dagsson-Waldhauserova et al., 2014). At Stórhöfði, also a dust sampler has been operated for many years. In contrast to the PM measurements presented in section 3.1.1, the long-term measurements at Stórhöfði only include dust. Except for the period December 1999 – June 2000, the measurements were set up to measure mineral dust from remote regions (during winds from east through south to west) rather than Icelandic dust. Some local dust events may therefore not be recorded at all or underestimate actual dust concentrations, as only the fraction that ‘returns’ when the wind shifts to a direction within the sampling sector is included. The observations should thus be seen as a lower estimate of dust concentrations.

Weekly mean values of modelled and observed dust concentrations are compared over a period of approximately 6 years in Figure 4. The dust at Stórhöfði likely originates mainly from the coastal dust sources in south Iceland (see Figure 1). The mean values of observations and simulation during the complete measuring period are  $8.9 \mu\text{g m}^{-3}$  and  $10.2 \mu\text{g m}^{-3}$ , respectively. The root mean squared error between model and observations is  $17.6 \mu\text{g m}^{-3}$ . For the period when sampling was not restricted to wind directions south through west, observed and modelled mean values are  $12.7 \mu\text{g m}^{-3}$  and  $11.7 \mu\text{g m}^{-3}$  respectively. We find that, except in 1999, the timing of peak dust concentrations appears to be very well captured by the model. This may be because these peaks represent large scale events rather than the activity of a few specific dust sources. Some events are modelled that do not occur in the measurements, but these appear to be limited in number compared to the results for fall events in Reykjavik. This suggests that the deviations in Reykjavik were restricted to specific dust sources. The peak events are mostly underestimated by the model. Some of these events are linked to glacial outburst floods (jökulhlaups) that can increase sediment supply, for instance in 1997 and 2000 (Prospero et al., 2012). Our model currently accounts only for a fixed but endless sediment supply, thus such temporary increases in sediment availability are not represented.

## 3.2 Dust emission

### 3.2.1 Spatial distribution

We show mean dust emissions calculated with FLEXDUST for the years 1990 through 2016 to understand which of the sandy fields are the most important dust sources. The long-term averaged emission map (Figure 5) identifies important dust sources in NE Iceland and along the south coast and shows a large similarity with soil fraction (Figure 1). Differences between soil fraction and emission patterns can occur due to snow cover, precipitation, storm occurrence and threshold friction velocity. For example, (north-) west of Langjökull glacier, much dust is emitted according to FLEXDUST because snow cover is less of a limiting factor here than in the interior highlands according to the ERA Interim data used in these simulations. In NE



Iceland, snow cover can inhibit modelled dust emission during winter season. At the south coast, precipitation has a larger influence on dust emission than snow cover.

In our model setup we accounted for dust hot spots that frequently emit dust and are assumed responsible for a large part of total dust emission in Iceland (Arnalds et al., 2016) by lowering the threshold friction velocity. In Figure 5, however, these  
5 dust spots are not recognizable as such. Their size is too small (in total approximately 400 km<sup>2</sup> of 16.7·10<sup>3</sup> km<sup>2</sup> active aeolian Icelandic sources) and dust emission in our simulations is not large enough that they could strongly influence the total annual dust emission in Iceland.

For dust emission, particular episodes of strong winds are very important. We therefore also infer on how many days per year dust sources are active. We look at dust hot spots Dyngjusandur and Landeyjasandur in particular, and at a sand field about 50  
10 km north of Dyngjusandur. Dyngjusandur was on average active on 302 days per year. On many days however, dust emission is only small, and 90% of total dust is therefore emitted in 145 days. Sporadic dust events account for the greatest fraction of emissions with 50% of dust emitted on only 37 days. This is particular for dust hot spots, characterised by soils with low threshold friction velocities. Further north of Dyngjusandur, in a ‘normal’ sandy field, some dust emission occurs on 227 days, but 50% of dust is emitted in only 26 days. Similarly in the south, we find that the Landeyjasandur dust hot spot is active on  
15 289 days, yet emissions on 38 days account for over 50% of annual dust emission. Looking at total dust emissions from Iceland, 50% is emitted in 25 days, and 90% in 110 days of the year. Previous studies of long-term dust frequency reported 135 dust days per year (Dagsson-Waldhauserova et al., 2014).

### 3.2.2 Interannual variability

Annual mean dust emission in the period 1990 until 2016 amounts to 4.3±0.8 Tg. This is similar to the FLEXUDST estimate  
20 for dust emission in Iceland in years 2010 through 2012 in global simulations (4.8 Tg, Groot Zwaafink et al. 2016). The estimated emission in 2012 is lower with ERA interim data (~2.9 Tg) than with hourly ECMWF operational data (~5.1 Tg). This demonstrates how resolution in time and space can affect our estimate of dust emission although other factors, like snow cover representation and the boundary-layer parameterizations in the meteorological model, also cause differences. Because dust emission has an approximate cubic dependency on wind speed, higher time and space resolution – which better captures  
25 maxima in wind speed– lead to systematically higher emissions. Dust emission rates are an order of magnitude lower than previous dust emission rates presented by Arnalds et al. (2014). Their estimate includes dust spikes and redistribution in relation to volcanic events and glacial outbursts and is in part based on deposition rates (soil metadata and tephrochronology). Also larger particles are included in estimates of Arnalds et al. (2014), most of which would be deposited in the near vicinity of their sources. Other possible causes for this large difference are the large uncertainty related to extrapolation of visibility  
30 and storm frequency observations to dust concentration and emission estimates. Such estimates are also highly dependent on observation locations. An under-estimation of dust activity from the localized hotspots in our estimate can also not be ruled out. Nevertheless, such high emissions as reported by Arnalds et al. (2014) would lead to strong overestimates of observed concentrations with our model.



The North Atlantic Oscillation (NAO) is an important mode of meteorological variability in the North Atlantic and Europe (Hurrell et al., 2013). To find out whether the NAO also influences dust emission in Iceland we plotted time series of annual dust emission and the annual station-based NAO index (retrieved from Hurrell & National Center for Atmospheric Research Staff, 2017) in Figure 6. With a coefficient of determination ( $r^2$ ) between annual dust emission and annual NAO index of 0.13 we find only a weak correlation. Distinguishing between dust emission from sources in south Iceland ( $<64.3^\circ\text{N}$ ) and north Iceland (see Figure 6, right panel) shows that dust emission in south Iceland more strongly correlates with NAO index ( $r^2=0.23$ ) than emission in north Iceland ( $r^2=0.10$ ). The lack of a substantial correlation between dust emission and NAO is consistent with conclusions of Dagsson-Waldhauserova (2013; 2014) based on dust storm observations that the main driver of dust events is probably a pattern orthogonal to NAO.

10

### 3.3 Aeolian transport and dust deposition

To understand where dust that is emitted from Iceland can be found in the atmosphere and on the ground, we look at maps of mean dust load in the atmosphere and deposition on the surface. As expected, dust loads are largest close to the sources (Figure 7), as much of the emitted dust is deposited after only small travel distances (Figure 8).

15 Patterns of dust load and dust deposition are naturally very similar. Since emission estimates were an order of magnitude smaller than estimates of Arnalds et al. (2014), deposition estimates are as well, but distribution patterns are similar. We also estimate especially large deposition rates in the Atlantic Ocean north-east and south of Iceland. Because dust emission is larger in northern Iceland (see Figure 6) and the main wind direction during dust storms in north east Iceland is from the south (Dagsson-Waldhauserova et al., 2014), much dust appears to be transported northwards. But also dust deposition south of  
20 Iceland appears considerable. The mean dust load and deposition patterns are consistent with a recent study of Baddock et al. (2017) showing three-day particle trajectories of dust storms from a location in north-east and south Iceland, calculated with HYSPLIT (Draxler and Hess, 1998) between 1992 and 2012.

To further understand what drives dust transport patterns, we look into correlations of monthly time series of dust emission, dust deposition and NAO index. In Figure 9a correlation between annual dust emission and annual deposition at each point is  
25 shown. Naturally, correlations are high close to dust sources where many large particles will be deposited. Away from sources the dust plumes spread and correlations become smaller. We find that especially in the region north-north-east of Iceland correlations are large. This may indicate that transport patterns do not diverge much here, only dust amounts. Given this large correlation, we have normalized dust deposition to annual dust emission for further analyses in Figure 9b and 9c. Correlations between dust emission in north-east Iceland and normalized deposition (Figure 9b) show a similar 8 (yet weaker) pattern as  
30 Figure 9a. Focussing on dust emission in south Iceland (Figure 9c), we find that correlations are generally weaker. The direction of dust plumes originating from these sources may be generally southwards, but probably varies much from south-west to south-east. Even though we find some relatively large correlations between dust deposition north-north-east of Iceland and dust emission in south Iceland, we do not think that these are strongly linked but are rather caused by dust emissions in





the north. The strong correlation between dust emission in north and south Iceland ( $r^2=0.67$ , also see Figure 6) means that we cannot properly separate influences of these two source regions on dust deposition in specific regions. Baddock et al. (2017) did study trajectories from either south or north Iceland and showed that dust from south Iceland was mainly transported southwards. Finally, even though we know that dust emission and NAO are not closely related (section 3.2.2), we investigate if dust deposition and NAO are. Transport of air pollution from Europe to the Arctic for instance is strongly linked to NAO (Eckhardt et al., 2003). However, Figure 9d shows that Icelandic dust deposition patterns correlate poorly with NAO.

### 3.4 Dust inputs to the ocean, glaciers and other regions

Dust occurrence affects marine and terrestrial ecosystems and the atmosphere and surface radiation balance. We therefore quantify the annual variability of Icelandic dust inputs to glaciers, the ocean and dust deposition in Greenland, Svalbard and Europe based on our model simulations. A large fraction of emitted dust ( $<20\ \mu\text{m}$ ) does not travel far and is deposited in Iceland. This fraction amounts to  $1.5 \pm 0.3\ \text{Tg}$  (Figure 10) or 34 % of annual emission. The consequences of such dust deposition in Iceland are very dependent on what type of surface is covered by the dust. For instance, correlations between dust deposition patterns and bird abundance are shown by Gunnarsson et al. (2015) and impacts of dust on Vatnajökull albedo and melt rates were discussed by Wittmann et al. (2017). We estimate that a considerable amount of dust is deposited on Icelandic glaciers (approximately  $0.2\ \text{Tg}$  or on average  $16\ \text{g m}^{-2}$ ). With glacier retreat and thinning, both horizontal and vertical distances of glacier areas to dust sources become smaller, causing enhanced dust deposition over the remaining glacier areas, as for instance also observed in a Holocene record of the Penny Ice Cap (Zdanowicz et al., 2000). This constitutes an important climate feedback mechanism. Figure 10 shows that interannual variability of dust deposition on Icelandic glaciers is similar to that of deposition in Iceland as a whole.

According to our simulations, most of the dust emitted in Iceland is deposited in the ocean. Simulated dust deposition to the ocean was on average  $2.5\ \text{Tg}$  or 58% of annually emitted dust. This estimate is much lower than the  $14\ \text{Tg}$  estimated by Arnalds et al. (2014), consistent with lower FLEXDUST emission rates. Much smaller fractions of emitted dust ended up in Greenland (2%) and Svalbard ( $<0.1\%$ ). Annual variability of dust deposited to the ocean closely follows dust emission. Annual dust deposition of Icelandic dust in Greenland is more variable. Probably conditions during single, particularly strong dust episodes have a large influence on dust deposition in Greenland. The same is true for deposition in Svalbard, where deposition was especially varying in the first years of our simulation period. From Figure 8 one can also infer that dust deposition amounts in Greenland are highly variable in space. Annual Icelandic dust deposition amounts at the Greenland east coast occasionally reach values up to  $1\ \text{g m}^{-2}\ \text{yr}^{-1}$ . On average however, dust deposition in Greenland is only about  $0.04\ \text{g m}^{-2}$ . Especially in north-west Greenland, Icelandic dust deposition amounts are low, with for instance mean deposition amounts of less than  $5 \cdot 10^{-3}\ \text{g m}^{-2}\ \text{yr}^{-1}$  at NEEM Camp ( $77.45^\circ\text{N}$ ,  $51.06^\circ\text{W}$ ). Most Icelandic dust stays in the near Arctic ( $>60^\circ\text{N}$ ), where on average about 78% of dust is deposited. However, only about 7% of emitted dust is deposited in the high Arctic ( $>80^\circ\text{N}$ ) in the years simulated in this study. The model confirmed that substantial amounts of Icelandic dust are deposited in the Arctic cryosphere and can influence surface albedo and melt in Iceland, Greenland and in other parts of the Arctic, as also suggested by Meinander et al.



(2016). Their hypothesis is that Icelandic dust may have a comparable or even larger effect on the cryosphere than soot (Bond et al. 2013).

#### 4. Conclusions

In this study we made model simulations of dust emission from Iceland over a period of more than two decades. The FLEXDUST emission model was slightly adapted for these simulations, such as through the inclusion of dust hot spots and the use of precipitation data to limit dust mobilization.

Simulations show that annual dust emission in Iceland amounts to  $4.3 \pm 0.8$  Tg on average in the years 1990 through 2016. These estimates are lower than values reported in the literature (e.g. Arnalds et al., 2014). Nonetheless, estimated dust emissions for the Icelandic sandy deserts (covering 22,000 km<sup>2</sup>, Arnalds et al., 2016) are approximately  $0.2 \text{ kg m}^{-2} \text{ yr}^{-1}$  and are comparable to estimated dust emissions in the western Sahara ( $0.1 \text{ kg m}^{-2} \text{ yr}^{-1}$ , based on Laurent et al., 2008). Moreover, annual Icelandic dust emissions account for ~0.3 % of global dust emission (Groot Zwaaftink et al., 2016). Annual variability of dust emission in Iceland showed a weak correlation ( $r^2 = 0.13$ ) with NAO index.

Transport model evaluation is based on dust and PM concentration measurements, even though the number of measurement stations in Iceland is very limited. Best agreement with PM measurements over one year is found close to dust sources. This indicates that the dust emission model works well, at least for the sources contributing mostly to those measurements. In Reykjavik, we found that model simulations perform well in spring, but include too many dust episodes in late fall and early winter, compared to PM<sub>10</sub> observations. This may be related to the dynamic behaviour of glacio-fluvial dust sources, which include areas where sediment availability is dependent on glacial floods. This complexity is typical for high-latitude dust sources (e.g. Bullard, 2013; Crusius et al., 2011), but currently not captured by FLEXDUST. Additionally, model evaluation based on PM observations is complicated by the inclusion of aerosol types other than dust. At Stórhöfði, near the south coast of Iceland, the timing of peaks in dust concentrations is very well captured in our simulations, as we determined based on a comparison of modelled and measured dust concentrations between 1997 and 2002. This suggests that the model is equipped to predict especially the large scale dust events.

In north Iceland dust transport patterns appear persistent, in south Iceland they are more variable. Emitted dust can travel over long distances, reaching Europe (3% of emitted dust) or Svalbard (0.1%). Much dust, especially large particles, is deposited close to dust sources and therefore stays in Iceland (34%). Glaciers in Iceland thus receive much dust (annually about  $16 \text{ g m}^{-2}$ ). Spatial variability of dust deposition on glaciers is large and dust is mostly deposited near glacier boundaries at low altitudes (also see Wittmann et al., 2017; Dragosics et al., 2016). Similarly, annually about 2% of Icelandic dust is deposited in Greenland, mostly at lower altitudes. Glacier retreat and thinning may thus be coupled to both an increase of dust source areas and decrease of the average distance of the glacier surface to dust sources, meaning a positive feedback between the dust cycle and melt rates.



Marine ecosystems and the carbon cycle may also be strongly affected by Icelandic dust. Most dust emitted from Iceland (58%) is deposited in the ocean, according to our simulations. Especially in regions north-north-east and south of Iceland deposition amounts appear considerable.

Our simulations indicate that most dust emission occurs in north-east Iceland. Unfortunately, this region is not covered well with observations and model verification is lacking. Future research should therefore also focus on these areas to improve descriptions of the dust cycle in Iceland and quantify impacts on the climate system.

### Acknowledgements

We thank Thorsteinn Jóhannsson (Environment Agency of Iceland) for providing the PM observations and discussions. We acknowledge funding provided by the Swiss National Science Foundation (grant 155294) and travel grants provided by the Nordic Centre of Excellence eSTICC (Nordforsk 57001). OA and PDW were supported by Icelandic Research Fund (Rannis) Grant No 152248-051 and PDW by The Recruitment Fund of the University of Iceland. The station at Storhofdi was initially established with support from the US National Atmospheric and Oceanic Administration to JMP and later sampling and analysis with support various grants from the US National Science Foundation (AGS-0962256).

### References

- 15 Achterberg, E. P., C. M. Moore, S. A. Henson, S. Steigenberger, A. Stohl, S. Eckhardt, L. C. Avendano, M. Cassidy, D. Hembury, and J. K. Klar, Natural iron fertilization by the Eyjafjallajökull volcanic eruption, *Geophysical Research Letters*, 40(5), 921-926, 2013.
- Arnalds, O., *The soils of Iceland*, 160 pp., Springer, Dordrecht, The Netherlands, 2015.
- Arnalds, O., P. Dagsson-Waldhauserova, and H. Olafsson, The Icelandic volcanic aeolian environment: Processes and impacts — A review, *Aeolian Research*, 20, 176-195, doi:http://dx.doi.org/10.1016/j.aeolia.2016.01.004, 2016.
- 20 Arnalds, O., F. O. Gísladóttir, and H. Sigurjonsson, Sandy deserts of Iceland: an overview, *Journal of Arid Environments*, 47(3), 359-371, doi:http://dx.doi.org/10.1006/jare.2000.0680, 2001.
- Arnalds, O., H. Ólafsson, and P. Dagsson-Waldhauserova, Quantification of iron-rich volcanogenic dust emissions and deposition over the ocean from Icelandic dust sources, *Biogeosciences*, 11(23), 6623-6632, 2014.
- 25 Baddock, M. C., T. Mockford, J. E. Bullard, and T. Thorsteinsson, Pathways of high-latitude dust in the North Atlantic, *Earth and Planetary Science Letters*, 459, 170-182, doi:http://dx.doi.org/10.1016/j.epsl.2016.11.034, 2017.
- Bond, T. C., S. J. Doherty, D. W. Fahey, et al., Bounding the role of black carbon in the climate system: A scientific assessment, *Journal of Geophysical Research: Atmospheres*, 118(11), 5380-5552, doi:10.1002/jgrd.50171, 2013.
- Bullard, J. E., Contemporary glacial inputs to the dust cycle, *Earth Surface Processes and Landforms*, 38(1), 71-89, doi:10.1002/esp.3315, 2013.
- 30



- Bullard, J. E., and M. J. Austin, Dust generation on a proglacial floodplain, West Greenland, *Aeolian Research*, 3(1), 43-54, doi:10.1016/j.aeolia.2011.01.002, 2011.
- Bullard, J. E., M. Baddock, T. Bradwell, J. Crusius, E. Darlington, D. Gaiero, S. Gassó, G. Gisladottir, R. Hodgkins, R. McCulloch, C. M. Neuman, T. Mockford, H. Stewart, and T. Thorsteinsson, High Latitude Dust in the Earth System, *Reviews of Geophysics*, 54, 447–485, doi:10.1002/2016RG000518, 2016.
- Crusius, J., A. W. Schroth, S. Gasso, C. M. Moy, R. C. Levy, and M. Gatica, Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron, *Geophysical Research Letters*, 38, doi:10.1029/2010gl046573, 2011.
- Dagsson-Waldhauserova, P., O. Arnalds, and H. Olafsson, Long-term frequency and characteristics of dust storm events in Northeast Iceland (1949-2011) (vol 77, pg 117, 2013), *Atmospheric Environment*, 79, 883-883, doi:10.1016/j.atmosenv.2013.08.007, 2013.
- Dagsson-Waldhauserova, P., O. Arnalds, and H. Olafsson, Long-term variability of dust events in Iceland (1949–2011), *Atmos. Chem. Phys.*, 14(24), 13411-13422, doi:10.5194/acp-14-13411-2014, 2014.
- Dragosics, M., O. Meinander, T. Jónsdóttir, T. Dürig, G. De Leeuw, F. Pálsson, P. Dagsson-Waldhauserová, and T. Thorsteinsson, Insulation effects of Icelandic dust and volcanic ash on snow and ice, *Arabian Journal of Geosciences*, 9(2), 126, doi:10.1007/s12517-015-2224-6, 2016.
- Draxler, R. R., and G. Hess, An overview of the HYSPLIT\_4 modelling system for trajectories, *Australian meteorological magazine*, 47(4), 295-308, 1998.
- Eckhardt, S., A. Stohl, S. Beirle, N. Spichtinger, P. James, C. Forster, C. Junker, T. Wagner, U. Platt, and S. Jennings, The North Atlantic Oscillation controls air pollution transport to the Arctic, *Atmospheric Chemistry and Physics*, 3(5), 1769-1778, 2003.
- Fécan, F., B. Marticorena, and G. Bergametti, Parametrization of the increase of the aeolian erosion threshold wind friction velocity due to soil moisture for arid and semi-arid areas, *Annales Geophysicae*, 17(1), 149-157, doi:10.1007/s00585-999-0149-7, 1999.
- Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik, and S. J. Lin, Sources and distributions of dust aerosols simulated with the GOCART model, *Journal of Geophysical Research-Atmospheres*, 106(D17), 20255-20273, doi:10.1029/2000jd000053, 2001.
- Groot Zwaaftink, C. D., H. Grythe, H. Skov, and A. Stohl, Substantial contribution of northern high-latitude sources to mineral dust in the Arctic, *Journal of Geophysical Research: Atmospheres*, 121(22), 13,678-613,697, doi:10.1002/2016JD025482, 2016.
- Grythe, H., N. I. Kristiansen, C. D. Groot Zwaaftink, S. Eckhardt, J. Ström, P. Tunved, R. Krejci, and A. Stohl, A new aerosol wet removal scheme for the Lagrangian particle model FLEXPART, *Geosci. Model Dev. Discuss.*, 2016, 1-34, doi:10.5194/gmd-2016-267, 2016.



- Gunnarsson, T. G., Ó. Arnalds, G. Appleton, V. Méndez, and J. A. Gill, Ecosystem recharge by volcanic dust drives broad-scale variation in bird abundance, *Ecology and Evolution*, 5(12), 2386-2396, doi:10.1002/ece3.1523, 2015.
- Hurrell, J. & National Center for Atmospheric Research Staff, "The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)." Last modified 17 Mar 2017, Retrieved from [https://climatedataguide.ucar.edu/climate-](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based)  
5 [data/hurrell-north-atlantic-oscillation-nao-index-station-based](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based), 2017.
- Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck, An Overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, edited, pp. 1-35, American Geophysical Union, doi:10.1029/134GM01, 2013.
- Kok, J. F., A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of  
10 the global dust cycle, *Proceedings of the National Academy of Sciences of the United States of America*, 108(3), 1016-1021, doi:10.1073/pnas.1014798108, 2011.
- Laurent, B., B. Marticorena, G. Bergametti, J. F. León, and N. M. Mahowald, Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database, *Journal of Geophysical Research: Atmospheres*, 113, D14218, doi:10.1029/2007JD009484, 2008.
- 15 Marticorena, B., and G. Bergametti, Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme, *Journal of Geophysical Research: Atmospheres*, 100(D8), 16415-16430, doi:10.1029/95JD00690, 1995.
- Meinander, O., P. Dagsson-Waldhauserova, and O. Arnalds, Icelandic volcanic dust can have a significant influence on the cryosphere in Greenland and elsewhere, 2016, doi:10.3402/polar.v35.31313, 2016.
- Prospero, J. M., J. E. Bullard, and R. Hodgkins, High-Latitude Dust Over the North Atlantic: Inputs from Icelandic Proglacial  
20 Dust Storms, *Science*, 335(6072), 1078-1082, doi:10.1126/science.1217447, 2012.
- Sodemann, H., T. M. Lai, F. Marengo, C. L. Ryder, C. Flamant, P. Knippertz, P. Rosenberg, M. Bart, and J. B. McQuaid, Lagrangian dust model simulations for a case of moist convective dust emission and transport in the western Sahara region during Fennec/LADUNEX, *Journal of Geophysical Research: Atmospheres*, 120(12), 6117-6144, doi:10.1002/2015JD023283, 2015.
- 25 Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa, Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2, *Atmospheric Chemistry and Physics*, 5(9), 2461-2474, 2005.
- Stohl, A., M. Hittenberger, and G. Wotawa, Validation of the lagrangian particle dispersion model FLEXPART against large-scale tracer experiment data, *Atmospheric Environment*, 32(24), 4245-4264, doi:http://dx.doi.org/10.1016/S1352-2310(98)00184-8, 1998.
- 30 Thorsteinsson, T., G. Gísladóttir, J. Bullard, and G. McTainsh, Dust storm contributions to airborne particulate matter in Reykjavík, Iceland, *Atmospheric Environment*, 45(32), 5924-5933, doi:http://dx.doi.org/10.1016/j.atmosenv.2011.05.023, 2011.



Wittmann, M., C. D. Groot Zwaaftink, L. Steffensen Schmidt, S. Guðmundsson, F. Pálsson, O. Arnalds, H. Björnsson, T. Thorsteinsson, and A. Stohl, Impact of dust deposition on the albedo of Vatnajökull ice cap, Iceland, *The Cryosphere*, 11(2), 741-754, doi:10.5194/tc-11-741-2017, 2017.

Zdanowicz, C. M., G. A. Zielinski, C. P. Wake, D. A. Fisher, and R. M. Koerner, A Holocene Record of Atmospheric Dust Deposition on the Penny Ice Cap, Baffin Island, Canada, *Quaternary Research*, 53(1), 62-69, doi:http://dx.doi.org/10.1006/qres.1999.2091, 2000.

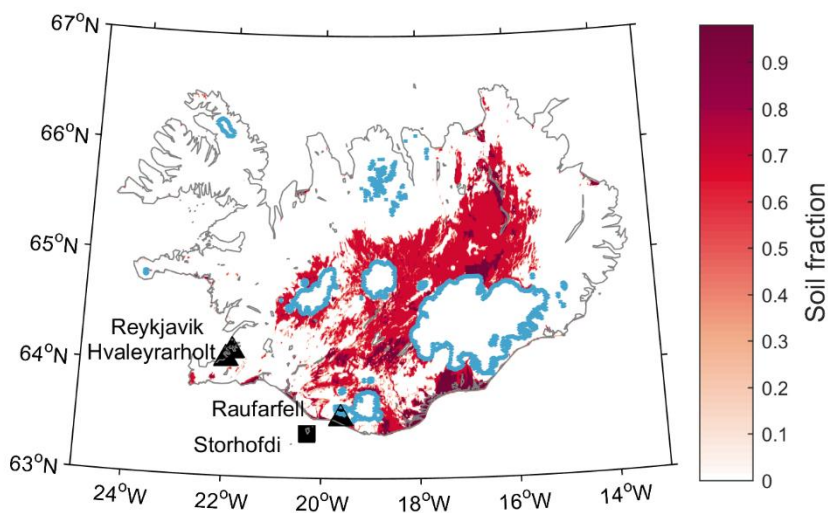


**Table 1** Threshold friction velocity based on observations presented by Arnalds et al. (2001) in each erosion class described by Arnalds et al. (2016).

Erosion class	Threshold friction velocity (m/s)
Dust hot spot	0.27
Extremely severe (5)	0.33
Severe (4)	0.58
Considerable (3)	0.70

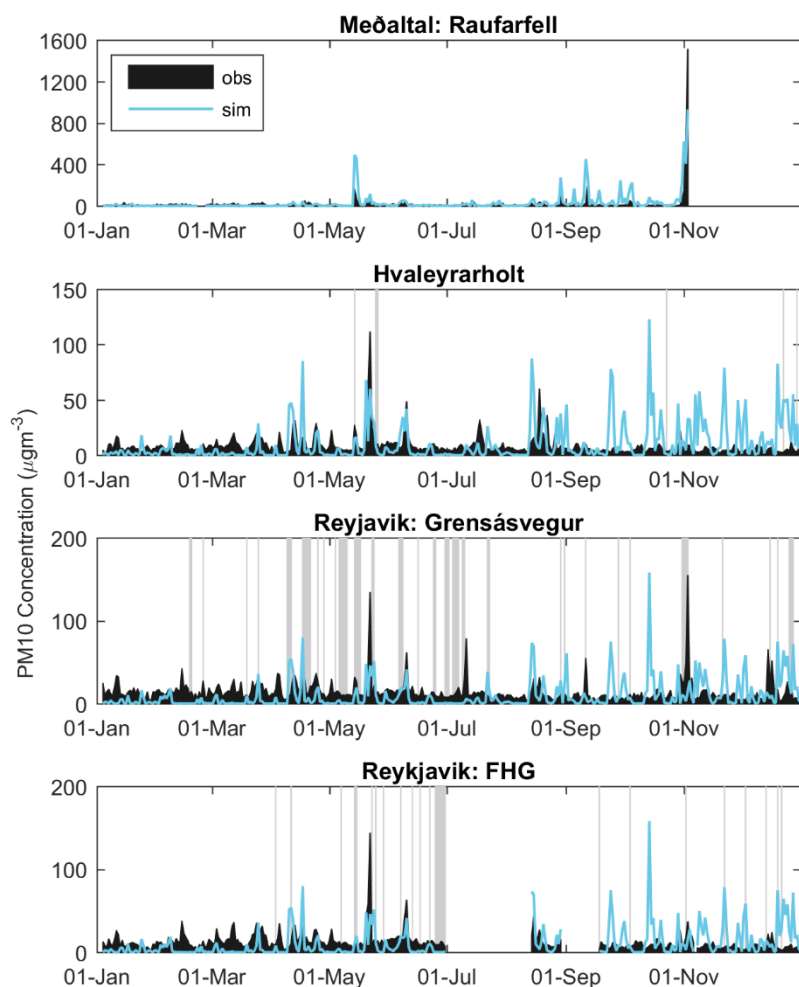
5 **Table 2** Statistics on observed PM10 concentrations ( $\mu\text{g m}^{-3}$ ) and simulated dust ( $d < 10 \mu\text{m}$ ) concentrations ( $\mu\text{g m}^{-3}$ ) at four stations in Iceland.

	Raufarfell		Hvaleyrarholt		Grensasvegur		FHG	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Median concentration	9	4	6	2	11	2	10	2
Mean concentration	21	28	8	10	15	9	13	10
Standard deviation of concentration	95	89	9	17	14	17	11	18
Number of days PM10 > 50 $\mu\text{g}$	13	31	3	17	7	16	3	14

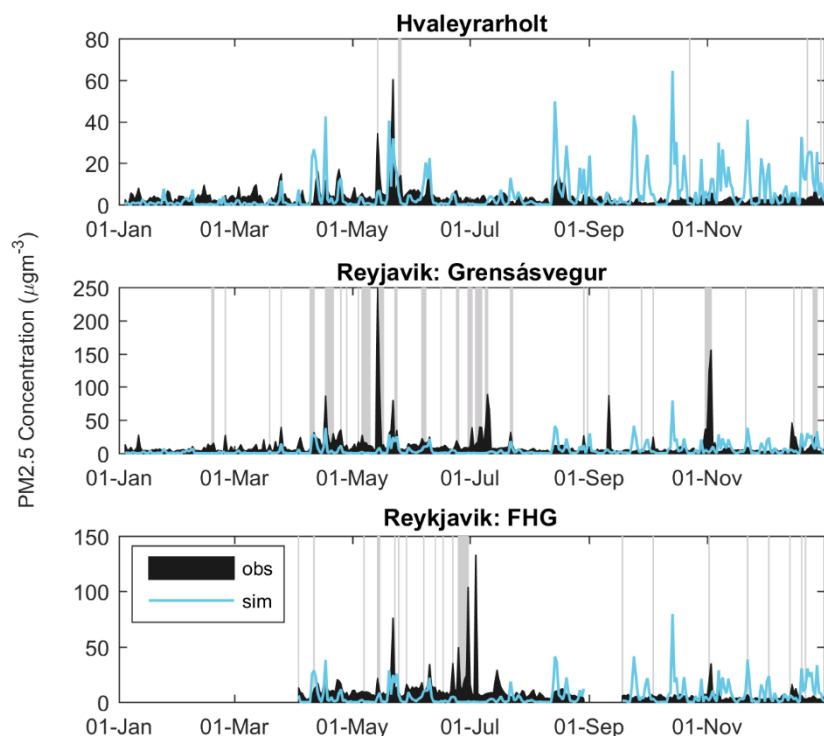


**Figure 1** Aeolian active soil fraction as assumed in FLEXDUST. The triangles indicate stations with PM measurements. The square marks the Storhofdi station with dust concentration measurements. The blue lines are glacier outlines.

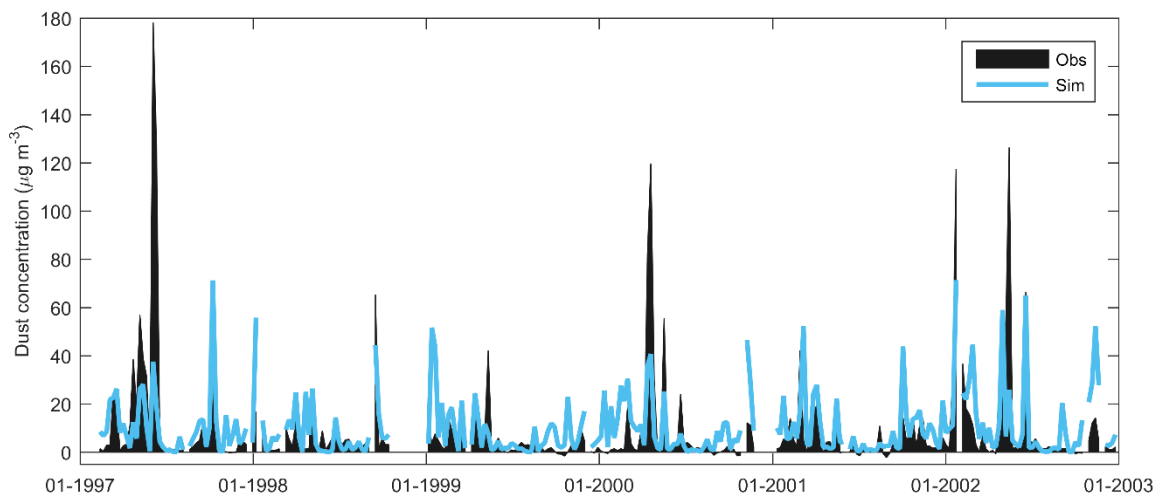




**Figure 2** Daily mean PM<sub>10</sub> concentrations ( $\mu\text{g m}^{-3}$ ) as observed (black) and modelled (blue) in 2012. Shaded grey areas indicate periods with inconsistent measurements of PM<sub>10</sub> and PM<sub>2.5</sub> (also see figure 3).



**Figure 3** Daily mean PM<sub>2.5</sub> concentrations ( $\mu\text{g m}^{-3}$ ) as observed (black) and modelled (blue) in 2012. Shaded grey areas indicate periods with inconsistent measurements of PM<sub>10</sub> and PM<sub>2.5</sub> (also see figure 2).



**Figure 4** Observed (black) and modelled (blue) weekly mean dust concentration ( $\mu\text{g m}^{-3}$ ) at Stórhöfði/Heimaey.

5

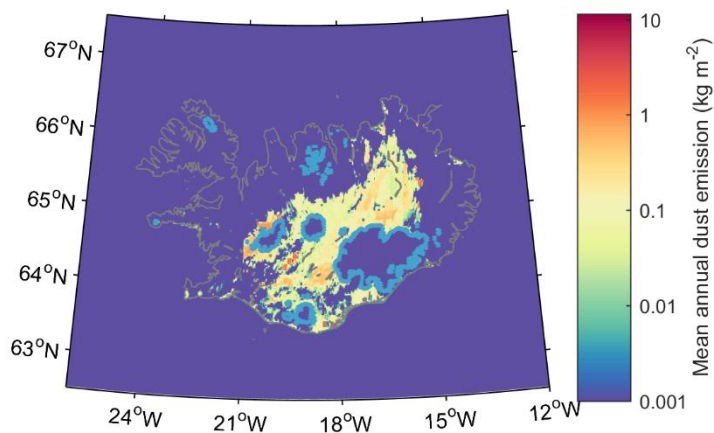
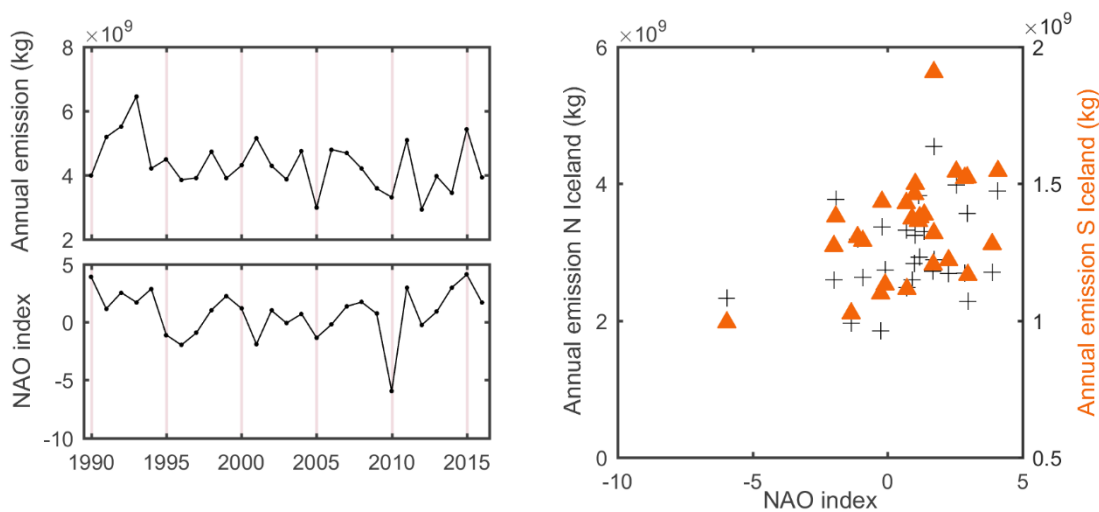
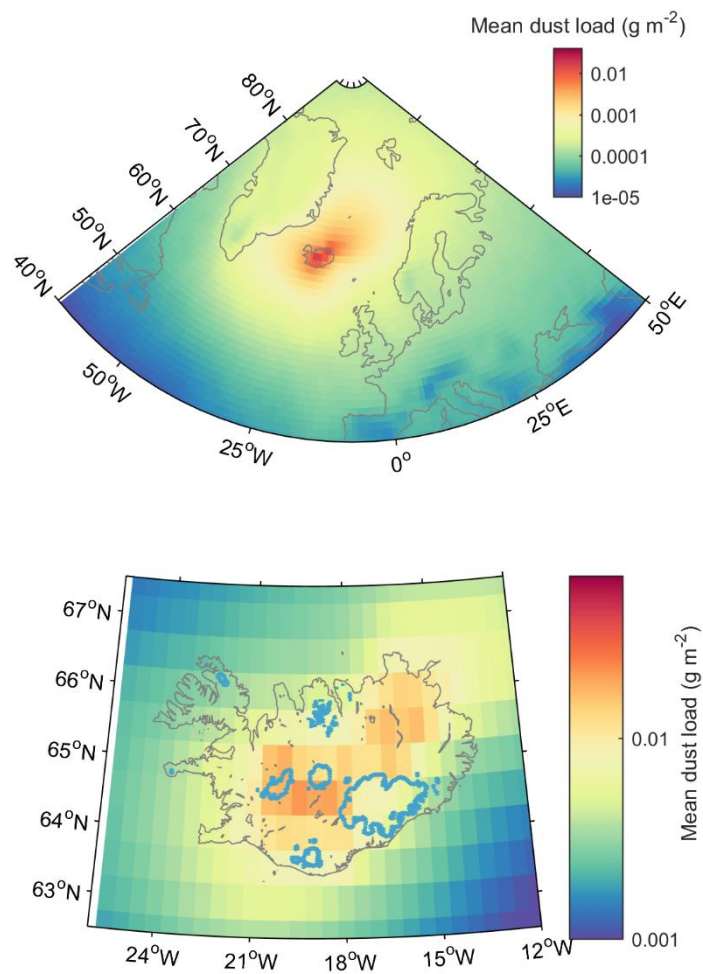


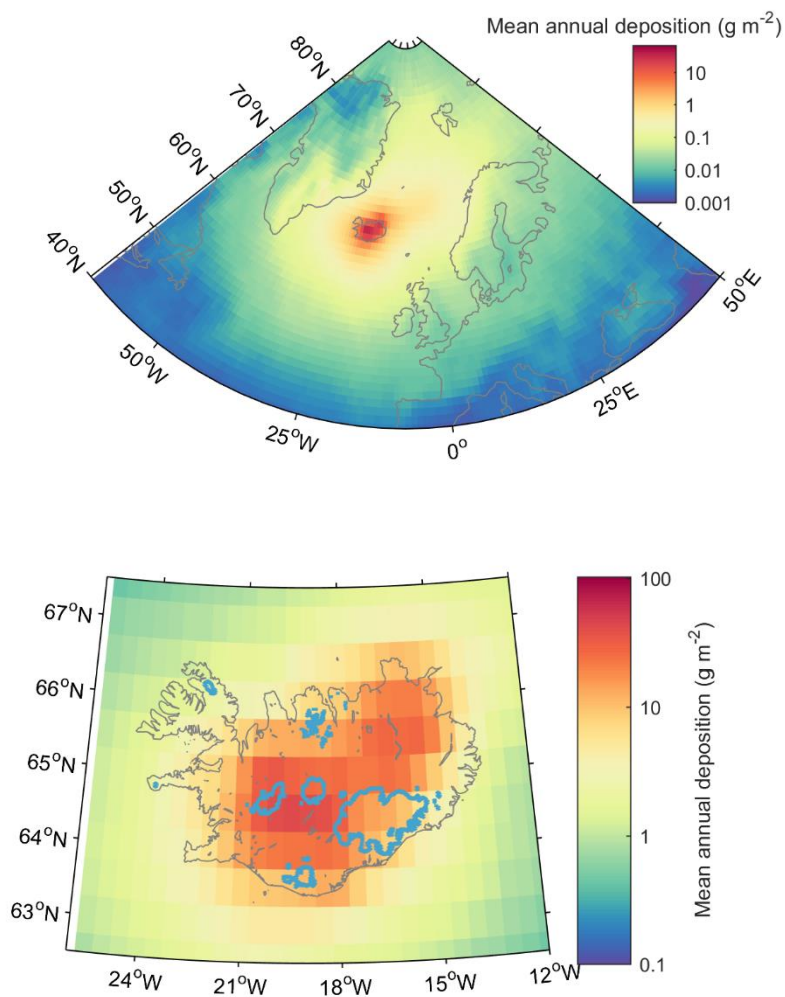
Figure 5 Simulated annual mean dust emission ( $\text{kg m}^{-2}$ ) in years 1990-2016



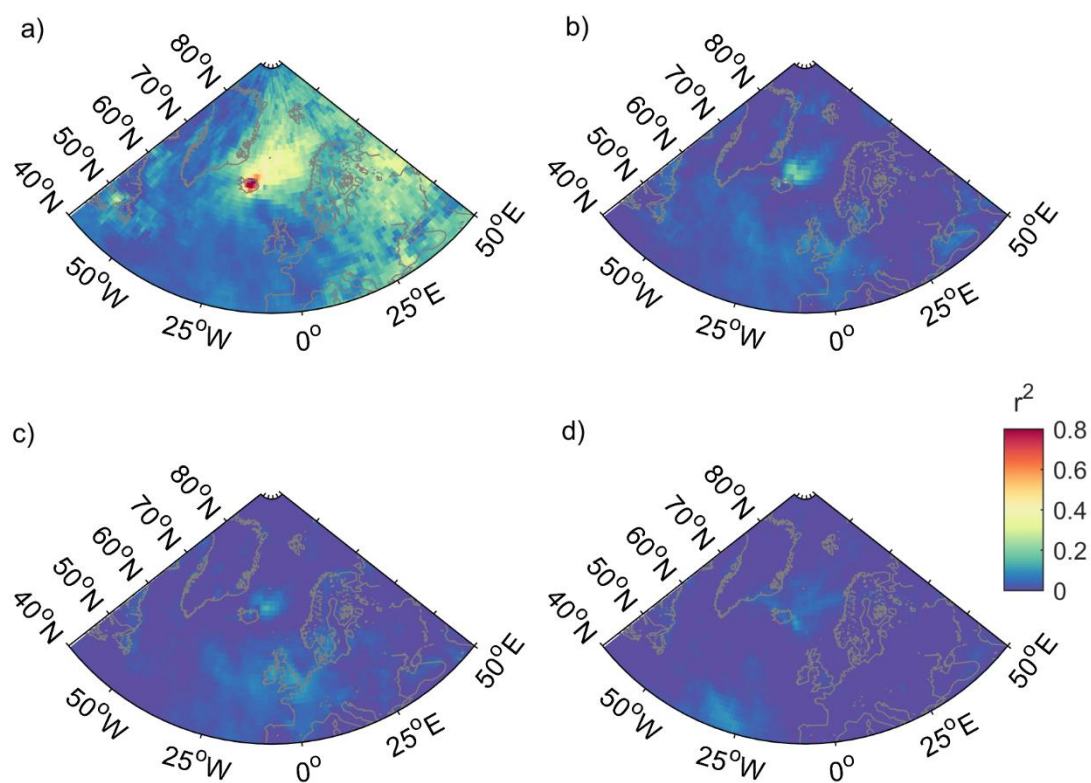
5 Figure 6 Left: Annual dust emission from Iceland in years 1990 until 2016 (top) and the annual NAO index (bottom). Right: Annual emission from Northern Iceland ( $>64.3$  degr. N) and southern Iceland ( $<64.3$  degr. N) versus annual NAO index.



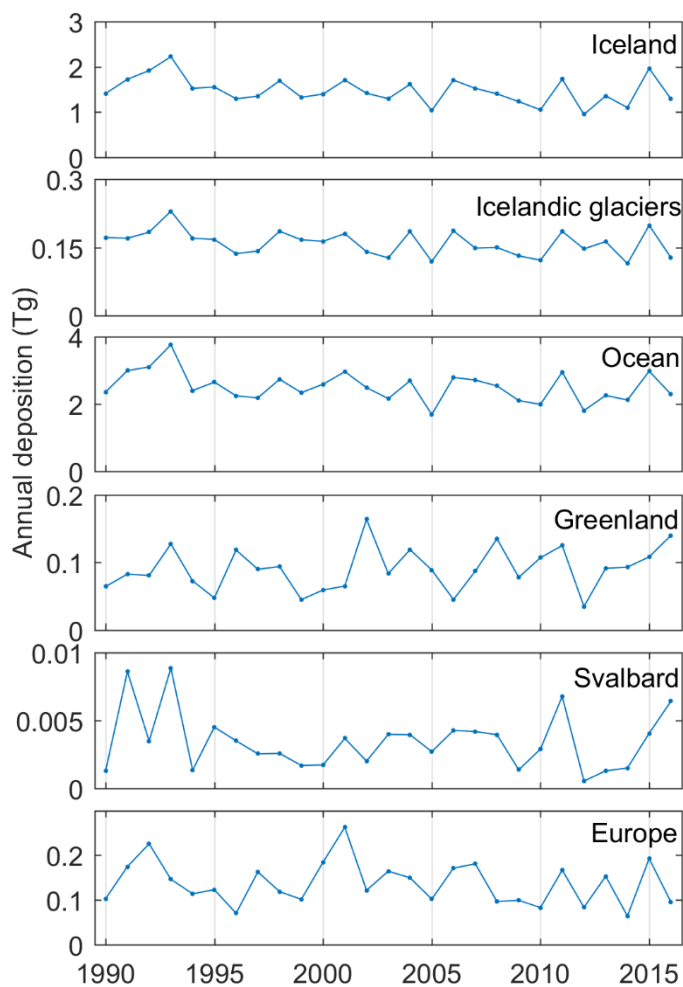
**Figure 7** Mean atmospheric dust load ( $\text{g m}^{-2}$ ) simulated with FLEXPART in years 1990-2016 for the North Atlantic region (top) and Iceland (bottom). The blue lines in the bottom figure are glacier outlines.



5 **Figure 8** Mean annual dust deposition ( $\text{g m}^{-2}$ ) simulated with FLEXPART in years 1990-2016 for the North Atlantic region (top) and Iceland (bottom). Maximum values are lower in the upper panel than in the lower panel as this figure shows averages over larger areas. The blue lines in the bottom figure are glacier outlines.



**Figure 9** Coefficient of determination  $r^2$  for monthly time series of dust deposition and emission (a), dust deposition normalized by total emission and emission in N Iceland (b), dust deposition normalized by total emission and emission in S Iceland (c), dust deposition and the NAO index (d).



**Figure 10** Time series (1990-2016) of modelled dust deposition ( $\text{Tg y}^{-1}$ ) in specific regions. Note that Iceland also includes deposition on Icelandic glaciers.