Interactive comment on “Temporal and spatial variability of Icelandic dust emission and atmospheric transport” by Christine D. Groot Zwaaftink et al.

Anonymous Referee #1

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RC: The authors present results from a muli-annual (27 years) study assessing the capability of the Lagrangian model FLEXPART to capture the Icelandic atmospheric dust life-cycle. Thereby, dust emission fluxes are estimated using FLEXDUST. Results of their study were further discussed regarding its interannual variability; results at high resolution were validated against measurements for the year 2012. The manuscript is well structured and a nice read. However, I do have some comments I would like the authors to address.

Authors: Thank you for your review.

2.1 Model description

(1) In the subsection FLEXDUST you describe how dust sources were implemented in the model. You state that lower friction velocities and large soil fractions were assigned to dust hot spots as identified by Arnalds et al. (2016). I am wondering whether these dust host spots occur due to enhanced levels of sediment supply or due to higher frequencies of stronger winds (maybe also channelled by orography).

Authors: The dust hot spots are known to be frequently active. Arnalds et al. (2016) ascribed this mostly to enhanced sediment supply, but also strong wind frequencies and soil properties (weaker winds can mobilize particles). Even without higher frequencies of stronger winds this already leads to larger dust emissions. To our knowledge no research has been published so far on strong wind frequency in dust hot spots.

(2) Can you spend some more words on how FLEXPART and FLEXDUST coexist respectively intertwine as this remains somewhat diffuse. As far as I understand FLEXDUST is used to estimate dust emission fluxes based on ECMWF forecast analyses at 0.2deg horizontal grid spacing. The calculated emission fluxes are then read into FLEXPART and transported whereby FLEXPART is driven using the ERA-Interim reanalysis at 1deg horizontal grid spacing. Why were two different atmospheric data sets chosen to drive the models rather than using consistently ECMWF forecast analyses for both but on a different horizontal grid?

Authors: Indeed FLEXPART and FLEXDUST are separate models. Our description of the simulation setup was obviously confusing. We always used the same ECMWF data for FLEXDUST and subsequent FLEXPART simulations. The high-resolution data were used for one year of model testing, whereas ERA-Interim data were used for the long-term simulations.
Changes: We changed the simulation descriptions in section 2.2 to clarify this.

(3) How is dust deposition respectively removal parameterized? Please add some explaining words. Is wash-out and scavenging due to rain and clouds considered as particle removal processes?

Authors: Yes, these processes are considered, as we mentioned in our manuscript: “In FLEXPART, simulated dust particles are influenced by gravitational settling, dry deposition and in-cloud and below-cloud scavenging (Grythe et al., 2016).“ Deposition processes are described in detail by Grythe et al. (2017) and for interpretation of the current study it suffices to know that these processes were included, we therefore choose to give a reference rather than a description. However, we added one sentence to explain a little better how removal processes are treated in FLEXPART: "Dry deposition is treated using the resistance method (Stohl et al., 2005), wet deposition distinguishes between liquid-phase and ice-phase scavenging (Grythe et al., 2016). "

(4) Simulation setup (section 2.2): As the input meteorological fields were available at a grid with a 0.2deg horizontal grid spacing, but dust emission fluxes were estimated on a grid with 0.01deg horizontal grid spacing, can you explain if there has been any upscaling or interpolation method applied, please? Is topography taken into account for the upscaling?

Authors: There was no upscaling involved for the meteorological fields, we use the 0.2 and 1.0 degrees grid values for the respective simulations. The surface type maps however, were available on a much higher resolution. Even though we use coarser-resolution wind fields, we can clearly define where dust emission occurs and this will give better initial conditions for Lagrangian modelling of particle trajectories. Notice that this method takes advantage of the Lagrangian nature of FLEXPART which is, in principle, independent of the resolution of the meteorological fields and thus can ingest emission data at any resolution.
Changes: We now comment on this in section 2.2.

3. Results and discussion
(5) In section 3.2.1, numbers of days of active dust emission are provided as fraction per annum. How do these numbers of days compare to seasons? Some additional sentences presenting and discussing the seasonal distribution of dust emission events, transport and deposition can help here to draw a more thorough picture of the Icelandic atmospheric dust life-cycle - and eventually imply further mechanism controlling interannual variability.
Authors: Modelled dust emission in Iceland is largest in winter/early-spring.
Changed: We added this to section 3.2.1.

(6) Is there any explanation why the NAO has no significant correlation with dust emission in Iceland?
Authors: It appears that the NAO index does not control dust storm frequency in Iceland. This was also concluded by Dagsson-Waldhauserova et al. (2014). Although we did not look at this in more detail, possible explanations may be found in increased precipitation or storm occurrence during seasonal snow cover.

(section 3.2.2)
(7) As stated in section 3.2.2, the NAO has no significant impact on dust emission. However, why is the NAO used as measure describing Aeolian transport and deposition patterns (section 3.3)? May topography has an important and maybe dominating impact on the transport direction here?
Authors: We hypothesised that even though emission is not linked to NAO, the transport patterns might be. For instance, pollution transport from Europe into the Arctic is strongly controlled by the NAO (Eckhardt et al., 2003). If dust would reach the south-east of Iceland where wind patterns (and thus transport patterns) correlate strongly with NAO, this might result in a correlation nonetheless. Even though no correlation was found, we think it is important to show this, as this was not clear a priori. Topography could be important as well as we also discuss in section 3.3 but we cannot explain this explicitly because we do not study transport pathways of specific regions.
Changes; We extended the discussion in section 3.2.2.

(8) How is the dust vertically distributed? Is there any significant dependency between dust deposition region and transport height or mixing depth into the boundary layer over source regions that can be concluded from the FLEXPART simulations? An enlarged discussion on dust transport pattern and deposition regions is desirable in order to clarify the conditions under which Icelandic dust is transported far beyond its source region. Furthermore, the results may vary with season as the predominance of meteorological situations (e.g. occurrence of precipitation, cloud formation) and atmospheric circulation patterns changes.

Authors: This is an interesting discussion, yet in our simulations we do not split dust from different source regions and we saved only limited data on the vertical distribution of dust. The modelled vertical distribution of Icelandic dust is limited. Global averages show that over 40% of suspended Icelandic dust is at altitudes less than 1000 m above the surface, thus probably within the atmospheric boundary layer. In averaged concentration fields only 6 % of suspended dust is situated at altitudes above 5000 m. Dust from the Hagavatn region has been observed at altitudes of 2 km and in LOAC (Renard et al., 2016a,b) vertical distributions dust reaches altitudes of 1 km during a dust-precipitation event in 2013 (not published).
Changes: We comment on the vertical distribution in section 3.3.

(9) Can the hypothesis by Meinander et al. (2016) that “Icelandic dust may have a comparable or even larger effect on the cryosphere than soot” be confirmed by the presented study?
Authors: This study confirms that Icelandic dust is likely to have an effect on the cryosphere and especially on the glaciers in Iceland, as can be concluded in combination with the results of Wittmann et al. (2017). However, this study was not set up to test this particular hypothesis and we would need to consider the complete cryosphere and include snowpack modelling influenced by soot as well as dust, and radiative transfer modelling. This may be a topic of further research.

Interactive comment on "Temporal and spatial variability of Icelandic dust emission and atmospheric transport" by Christine D. Groot Zwaaftink et al.

Anonymous Referee #2

Received and published: 18 May 2017

This compact paper, "Temporal and spatial variability of Icelandic dust emission and atmospheric transport" presents surface observations and results of lagrangian simulations of dust emission and deposition at high resolution for 2012 and lower resolution for 1990-2016 to estimate the dust emission and deposition to the region. The paper is very well written, presents interesting results from modeling and the observations, and references the appropriate literature. I believe that details are lacking in places and the analysis is a little weak, namely the comparison with observations and the certainty with which the dust emissions can be estimated, and would like to see those parts improved prior to publication.

General comments

The PM10 and simulated dust concentration yield similar mean (21 ug/m3 and 28 ug/m3, respectively) and standard deviations (pg 5 line 10); however, this is comparing dust-only concentrations from the model with bulk aerosol PM10. This suggests that the simulated dust concentrations are actually biased high (maybe up to a factor 2?) relative to the observations (if the non-dust component could be removed from the PM10). I think the way that the model results are compared to the PM10 (and PM2.5) may need reconsidering or the present method better justified. Can you estimate the non-dust component? How much of the PM10 at the sites may be localized dust that would not be captured by the model? This affects the attempt to estimate the annual emissions from Iceland and subsequent deposition. I'm not sure whether the current observational constraints and analysis are able to fully support the estimate. The agreement with the dust concentration measurements seems reasonable at StórhöfÃˇri, but this is only a single measurement site SW of the source regions. Therefore, the constraint on emissions transported in other directions is weak; it appears that equal, if not great, dust mass is deposited to the NE. Could the statistical relationship between observations and modeled dust concentration be used to better estimate the emission, or at least the uncertainty? For example, how much would the emissions need scaling to provide the same average dust concentration (or some other metric) at StórhöfÃˇri? this suffers from the lack of constraints for the dust in the NE, but might give a better representation of the dust emissions and their uncertainty beyond the interannual variability.

Authors: Thank you for your review. Indeed the constraints on dust emission in Iceland are weak. This results from the paucity of available data in Iceland and, to our knowledge, we have used all data that are available to compare our simulations with, even if most of the measurements (especially the PM measurements) do not allow direct comparisons. In the paper, we simply tried to use the long-term measurements that are currently available and also suggest that future more specific measurements would be needed to quantify the apparently important Icelandic dust sources. PM10 and PM2.5 values include other aerosols. This is of less concern at Raufarfell where traffic and sea salt influence are considered limited, but of larger concern in domestic and coastal areas as discussed in section 3.1.1. We therefore give more emphasis to the measurements at Storhofdi that only include dust. Close to the dust sources in NE Iceland we could confirm deposition rates based on snow sample observations (Wittmann et al., 2017). Other quantitative data is unfortunately not available and there are also no other supportive data that would allow a speciation of the PM data into different aerosol types. With the current data we can only conclude that timing of dust events can be captured and that dust deposition and concentrations, and therefore expectedly dust emission, are on the right order of magnitude. More precise estimates on these scales are currently not feasible, yet the model does provide an upper constraint.

Changes: we added and discuss references on different sources causing PM10 values exceeding health limits in Reykjavik and aerosol concentrations (other than dust) at Storhofdi in section 3.1.1.

Following from this, I can't see any comparison of the low and high resolution runs in 2012 (other than 2.9 Tg and 5.1 Tg totals for 2012 on pg7, line 21). Does this mean that running at high resolution may give 75% higher emission estimates than the 4.3+/- 0.8 Tg presented for the long term estimates? I don't

think the implications of this are discussed clearly enough. The uncertainty estimate for the interannual variability may mislead the reader to the certainty of the magnitude of the dust emissions (and hence deposition). Does the low resolution run well-reproduce the high resolution simulated dust concentration timing in 2012 otherwise? Maybe add the low resolution timeseries at StórhöfÃˇri to Figure 2?
Authors: In 2012 emission estimates were higher based on high resolution data. Deviations are also likely for other years. The measurements at Storhofdi are not available in 2012, instead we now discuss the high and low resolution runs in comparison to the PM10 measurements.
Changes: we provided additional results from the low-resolution simulation and extended the discussion on the influence of resolution in section 3.1.1.

While the time series of concentration provide a good visual reference of the frequency and magnitude of events, they are not ideal for illustrating the agreement between the simulation and the observations. I recommend providing a scatter-plot (perhaps on a log-log scale?) to better illustrate how well the model captures the observations of dust concentration. This is less useful (and therefore perhaps less necessary) for the comparison with PM for the reason outlined above, unless speciation is available.
Authors: We agree that this is useful for the dust concentrations, in combination with the time series already given.
Changes: We added such a figure for the Storhofdi data.

Emissions are not allowed when the precipitation rate is above the 1 mm/hr threshold. Is there a lag time for this emission suppression after the rain stops? Or is it expected that the timescale for the surface drying and becoming an active once again is shorter than the model timestep? How much do you think this assumption affects the emission?
Authors: In FLEXDUST, there is no time lag suppressing dust emission after rain. In a model test case where dust emission is prohibited if the precipitation sum in the past 4 hours exceeds 2 mm the model failed to simulate some strong dust events that were recorded in PM10 measurements. We therefore assume that during strong wind conditions the top sediment layer is quickly dried and dust emission is possible. This assumption is confirmed by several observations. Dagsson-Waldhauserova et al. (2014b) observed dust mobilization of wet particles, even during low-wind conditions. They discussed that the relatively dark basaltic dust might dry quickly. Also during intermittent snowfall dust mobilization has been recorded (Dagsson-Waldhauserova et al., 2015). Furthermore, analysis of long-term weather observations of dust events (e.g. Dagsson-Waldhauserova et al., 2014a) revealed that suspended dust is observed during precipitation events, although it is noted that precipitation at the weather observation location does not necessarily imply wet conditions at the dust source.
Changes: We added a model test for PM10 concentrations at Raufarfell and discuss the model results and references in section 3.1.

In Groot Zwaaftink et al. (2016) it is stated that, relative to a precipitation threshold, "Especially in northern latitudes, soil moisture appeared a better indicator of mobilization threshold as seasonal variations in surface dust concentrations at remote stations were better captured and total emission amounts were closer to other model estimates." Please can you comment on why this is different to the current research findings for Iceland.
Authors: The global simulations were based on a combination of size-dependent friction velocity thresholds (Shao and Lu, 2000) and increase of threshold friction velocity due to soil moisture according to Fécan et al. (1999). Instead, we here use friction velocities from field observations in Iceland. The combination of these observed thresholds with the soil moisture parameterization of Fécan et al. (1999) lead to very low dust emission rates and dust concentrations far below the measured values shown in section 3.1, as also discussed in our manuscript. Dagsson-Waldhauserova et al. (2014b) noted that the relatively dark basaltic dust of an Icelandic dust source dried quickly and dust mobilization occurred during moist conditions. It could thus be that Icelandic dust mobilization is less dependent on soil moisture and the soil moisture parameterization (Fécan et al., 1999) is not applicable. Furthermore, the ECMWF soil moisture data might not be representative for the layer from which dust is mobilized.
Changes; we extended the discussion on the soil moisture parameterization in section 2.1.

Specific Comments
pg 3 line 18 - "FLEPXART" typo
Authors: Corrected
pg 7 line 19 "FLEXUDST" typo
Authors: Corrected

It may be clearer to refer to the "soil fraction" as the "bare soil fraction" throughout.
Authors: Yes, that's better, we changed this.

Table 1 - it isn't quite clear how these values are derived from the threshold friction velocities presented in Arnalds et al. (2001) and the discussion in Arnalds et al. (2016). Please can you elaborate in the text on how these values are derived.
Authors: We added the explanation below in section 2.1.
Changes: We use observations from Arnalds et al. (2001) and a description of erosion levels (Arnalds et al., 2016) to determine the threshold friction velocity (see Table 1). While Leadbetter et al. (2012) and Liu et al. (2014) chose a fixed threshold friction velocity of 0.4 m s-1 for mobilization of volcanic ash, the range of values applied here is more suitable to cover the different conditions of multiple dust sources. Arnalds et al. (2016) give an overview of erosion classes for each surface type. For regions with extremely severe erosion we assume the average of threshold values observed at several sand fields, for severe erosion we assume average conditions of sandy gravel and for considerable erosion we apply an upper threshold observed for sandy gravel (Arnalds et al., 2001). 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), corresponding to the lowest threshold wind velocity estimates for erosion by Arnalds et al. (2016), and a slightly larger bare soil fraction (+3%).

Figure 2 - The Raufarfell timeseries is hard to see because of the upper limit. Is it possible to use a discontinuity on the y-axis above _600 ug/m3 to better visualize the data at lower concentrations.
Changes: We changed the figure accordingly.

Interactive comment on "Temporal and spatial variability of Icelandic dust emission and atmospheric transport" by Christine D. Groot Zwaaftink et al.

F M Beckett (Referee)
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The paper presents a modelling study of the emission and transport of dust in Iceland between 1990 and 2016. It highlights the significance of high latitude dust sources on the global dust budget, and the authors present interesting results showing the main transport pathways of dust from Iceland. However, I believe the description of the model set-up needs to be significantly improved before this paper can be published. Details, including a description of the resolution of the model topography used and the particle size distribution applied are missing, and there needs to be some discussion on how their results may be sensitive to their set-up. The manuscript would also be improved by including some discussion on how the supply of new dust sources, related to volcanic eruptions in Iceland, might influence their results.
Authors; Thank you for your constructive review.

1. The Introduction
I can see the importance and relevance of this study but I don't think this is reflected in the introduction. Details are missing and statements are often not backed up with existing data and/or references are missing. Currently, it reads as a series of statements rather than explaining to the reader why the study is important, the approach, and how it fits in with the existing literature. You need to discuss in more detail the work that has previously been carried out to better understand dust emissions in Iceland, including work published by Olafur Arnalds and Pavla Dagsson-Waldhauserova, and you should consider work on dust events in other parts of the world too. Further discussion on modelling dust emissions is also needed. You state that model simulations of dust emissions in Iceland are lacking but there is now a body of work on modelling remobilisation of volcanic ash in Iceland, see Leadbetter et al. (2012), Liu et al. (2014), Beckett et al. (2017), and further afield, for example Folch et al. (2013) and Mingari et al. (2017) who consider remobilization in Argentina. Given that volcanic ash is a significant source of PM in Iceland (indeed there is the question of what is dust and what is ash!!), and the modelling approaches for remobilized ash are very similar to the approach you have applied here you should discuss this.
Authors; Indeed the modelling efforts considering remobilisation of volcanic ash are relevant and are now included in the introduction. We also added more details on current knowledge of Icelandic dust, although we refer to a recent review paper by Arnalds et al. (2016) for a complete overview.

Specific comments:
Line 3: You state that: 'Model simulations indicated that 0.3% of global dust emission may originate from Iceland (Groot Zwaaftink et al., 2016)'. More details are needed here, what model, what simulations were performed and with what aim? If this has already been done then where does the study you are about to present fit in?
Authors; These were global simulations over a three-years periods where spatial distribution of dust emission in Iceland was not discussed.
Changes; We give additional details on this reference.

Line 4: You state that 'it is known that dust storms frequently occur there [Iceland]' and cite Dagsson-Waldhauserova et al. (2014). It would be good to include some numbers here e.g. how many dusty days, on average, occur in Iceland. This will help put your results into context later on too. I realise you comment on this later in the paper but this should be here in the Introduction.
Authors; We added this information in the introduction.

Line 14: You need to provide a reference for the surface type map that you refer to.
Authors: Added.

2. Model Set Up
The explanation of your model set-up is missing many details. I think you should include the equations used in FLEXDUST to model the emission of dust, and explain the variables. Exactly how does your model set-up account for topography, snow cover and soil moisture? You state that precipitation halts mobilization. You need to refer to the work of Leadbetter et al. (2012) here who also considered how best to represent the impact of precipitation on mobilization of volcanic ash in Iceland. Please can you also comment on how well you think this approach is working in respect to representing the timing and frequency of dust events? This is discussed by Leadbetter et al. (2012) and Liu et al. (2014) who both point out that this approach does not account for wetting and drying of volcanic ash deposits, do you think this is true of all dust sources?
Authors; FLEXDUST equations have been given in Groot Zwaaftink et al. (2016) and we do not think this should be repeated here. We rather concentrated our presentation of FLEXDUST on the differences in the model set-up used in the present paper from the one used by Groot Zwaaftink et al. (2016), although we agree that a little more detail will be helpful for the reader. Indeed precipitation influences dust mobilization, as is accounted for in the model and we agree that more discussion on this topic is useful.
Changes: We added equation 1, which gives the dependency of dust emission on (threshold) friction velocity. We now refer to these studies on mobilization of volcanic ash in sections 1 and 2. We also added results of a test simulation where we included a drying period after precipitation that showed dust mobilization was not better represented near the source by inclusion of such a time lag. We also slightly extended the general description of FLEXDUST.

Please provide the Particle Size Distribution (PSD) you used and explain your reasoning for this choice. Why did you choose to consider particles with diameter up to 20 um only? What is the minimum particle size you considered? The work of Liu et al. (2014) gives the PSD of ash particles that had been remobilized and deposited in Reykjavik during March 2013. They found that particles had a mode at 32-63 um. Have there been any measurements of the PSD of particles mobilised from the other dust sources in Iceland?
Authors; We considered particles in the size range 0.2 to 20 µm, consistent with global dust simulations using FLEXDUST and FLEXPART (Groot Zwaaftink et al., 2016). The size distribution is provided in the given references. It is quite standard to consider only particle sizes less than20 µm in dust modelling (e.g. Tegen, 2003). Observations of size distributions in Icelandic dust storms show that particle mean diameter is much smaller than 10 µm (Dagsson-Waldhauserova et al., 2014b). Larger particles may be present close to the sources but their potential for atmospheric transport away from the source region is very limited, due to rapid gravitational settling. As our focus is on dust transport, we do not include such large particles in our simulations.
Changes: we added the minimum particle size to section 2 and discuss observed particle size distributions.

3. Thresholds Friction Velocities.
Please provide your reasoning for the threshold friction velocities that you apply. How were these values determined from the Arnalds et al. (2001) and Arnalds et al. (2016) papers and how are the classes defined? Please also provide information on how these classes are distributed across Iceland. Figure 1 shows the soil fractions applied but please also highlight where the Dust Hot Spots are and how the erosion classes are applied across the other source regions. Please can you also comment on how good a job you think these threshold friction velocities are doing. By applying this range of values are you doing a good job of representing the timing and frequency of events in your model output? How sensitive is your model output to the threshold friction velocity applied? Can you account for some of the mismatch between the observed and modelled PM10 and PM2.5 air concentrations if you vary the threshold friction velocity applied?

Authors; The erosion classes have been presented in several publications (Arnalds et al., 2001; 2014; 2016) and are therefore not repeated here. The dust hot spots are the regions with maximum soil fraction in Figure 1. The threshold friction velocity affects timing and frequency of dust events and the concentration during events, as is now also clear from equation 1. Some of the mismatches are likely related to threshold friction velocity, we expect mostly because we use a fixed threshold (besides precipitation and snow cover influence). The threshold friction velocities of several sources are probably changing over time, even during dust events the surface conditions are changing. Despite the strong simplifications we apply in our model, we are able to capture timing of several events.
Changes; We added equation 1, which shows dependency of dust emission on threshold friction velocity. We added an explanation on the thresholds for each erosion class and a discussion in section 2.1. We discuss the influence of threshold friction velocity on results in sections 3.1.1, 3.1.2 and 4.

4. Topography
What is the resolution of your model topography? Are your results sensitive this? You state in the introduction that dust events can be driven by katabatic winds; does your model topography allow you to capture these meteorological phenomena? Mingari et al. (2017) show how the topography in Argentina influences the local winds and in turn how that drives mobilization. I think you need to consider this. This information would help put in context your later comment in Section 3.1.1 that the model output may not be able to capture observed PM10 concentrations because of the resolution of the topography.
Authors; The topography resolution is the same as in the ECMWF wind fields, thus 0.2 degrees for the high-resolution simulation and 1 degree for the long-term simulations. Indeed we cannot capture all local winds and discuss this in our manuscript.
Changes: We now already introduce this potential problem in section 2. We also add a discussion on sensitivity to model resolution in section 3.1.1.

5. Sources
You compare your model output air concentrations to PM data from monitoring stations across Iceland collected during 2012. You state that: 'In this year no volcanic eruptions occurred that could strongly influence PM measurements' (Line 8, Section 2.3). I disagree. Do you really think that the ash deposits from the eruption of Grimsvotn only the year before and from Eyjafjallajökull in 2010 had all been removed and were no longer a significant source of PM? The study by Leadbetter et al. (2012) considers the remobilization of volcanic ash from the deposits resulting from the eruption of Eyjafjallajökull in 2010. They compared modelled air concentrations using the dispersion model NAME, which includes a resuspension scheme, to PM10 measurements across Iceland during September 2010 to February 2011. Their modelled concentrations agree well with the timing and location of observed peaks in the PM10 data from the monitoring stations, and here only the Eyjafjallajökull ash is defined as the source. I recognize that your study aims to consider the long-range trends of dust emission and transport from sources across Iceland, but I think you need to acknowledge the fact that volcanic eruptions result in significant new sources of unconsolidated deposits which can continue to be remobilized for years after an eruption. In Section 3.2.2 you go on to state that your modelled dust emission rates are an order of magnitude lower than previous estimates given by Arnalds et al. (2014), and you say this could be related to volcanic events. I would suggest that you could explore this further and consider that the deposits from the Grimsvotn and Eyjafjallajökull eruptions could be a significant source of PM in your study.
Authors; We mainly wanted to avoid influence from direct injection of volcanic ash into the atmosphere. Resuspension of deposited tephra should be included in FLEXDUST, so in principle does not constitute a problem. Iceland, generally, is highly dynamic and land cover changes in response to volcanic eruptions and as deposited tephra fields age. In 2012, there was no volcanic eruption in Iceland, but of course ash deposits from previous years may still be remobilized. In fact, the dust sources in our surface type map are partly covered with fresh tephra. Also ash from the Eyjafjallajökull and Grimsvotn eruptions were partly deposited on active dust sources that are included in our model, even though our land cover map does not account for any changes due to the recent eruptions. This means that we partly include resuspension of volcanic material. This should indeed be included as a discussion and we added this in sections 2 and 4.

6. The impact of NAO
I did not follow why you chose to consider the role of NAO as part of your study and what the significance is? What meteorological variables and/or synoptic conditions related to NAO do you think impact mobilization events in Iceland?
Authors; The winter Icelandic low is stronger during NAO positive phases according to model simulations (Bromwich et al., 2005) and this relates to precipitation, temperature and wind in Iceland. Stronger winds can enhance dust mobilization, while precipitation and snow cover can inhibit dust mobilization. We thus wanted to know if dust emission amounts are related to NAO. Furthermore, stronger winds over the North Atlantic can increase dust transport.
Changes: We changed the discussion on NAO in section 3.3.

Minor Comments
In several places, including in the abstract, you state your conclusion that: 'Annual dust emission amounts to 4.3_0.8 Tg during the 27 years of simulation'. I find the term 'amounts to' a little confusing when discussing the yearly average. Please clarify.
Changes; we rephrased where applicable.

Page 1, Line 3. Emission should read emissions.
Authors: rephrased

Page 1, Line 19. 'A model for estimates of dust emission', does not read very well. The structure of this sentence needs to be improved.
Changes; rephrased.

Page 1, Line 26. Please provide references for your examples on the impacts of dust.
Authors; we provide references later in the introduction.

Page 2, Line 14. '.......surface type map of Iceland to identify dust sources'. I think you need to cite Arnalds et al. (2016) here.
Changes; we added an appropriate reference.

Page 2, Line 21. I did not quite follow this sentence: ' ....and originally accounts for snow cover, topography....' . What do you mean by 'originally'?
Authors: It does in the global setup where the model was first introduced, but this differs in the Iceland version.
Changes; rephrased

Page 3, Line 3. 'As we here mainly deal with sediments'. What do you mean by this statement, what is the relevance of 'sediments' is this different to 'dust'. Please clarify. Also the structure of this sentence could be better, what do you mean by 'mainly deal with'?
Changes; Rephrased this section.

Page 3, Line 8. What do you mean by a 'closed snow cover'?
Authors; A snow cover that does not consist of snow patches but covers the area.

Page 3, Line 17. 'as was previously also done for'. Could read better, how about 'and has previously been used to model the transport of Saharan dust'.
Changes: rephrased

Page 3, Line 21. What do you mean by a 'multitude of particles'? Please be specific.
Changes: rephrased

Page 4, Lines 1 and 2. Here you write the units of the particle size (micrometre), in other places you use the symbol. Please correct. Also, the structure of this sentence could be improved.

Changes: rephrased

Page 4, Line 17. ‘Model evaluation is limited due to a lack of data.’ This sentence does not read well. Please improve the structure of this paragraph.
Changes: rephrased

Page 4, Line 19. Should read ‘......concluding that THE modelled spatial distribution.....’.
Changes: rephrased

Page 5, Line 3. What are the problems with the sensors that you refer to?
Authors; there were different problems, but further details will not improve understanding of the results.

Page 5, Line 12. ‘....and are at larger distance from dust sources, and shorter distance to the ocean’, does not make sense. How about ‘...and are further away from the dust sources, and closer to the ocean.’
Changes; rephrased.

Page 5, Line 25. ‘rather too large in the model’. How about instead ‘.... are overestimated in the model output’.
Changes: rephrased

Page 6, Line 4. Please explain where Storhofdi is in order to put the rest of the discussion in Section 3.1.2 into context.
Changes: rephrased

Page 6, Section 3.1.2. I think you need to cite the work of Prospero et al. (2012) here.
Changes: rephrased

Page 6, Line 25. Here you refer to ‘sandy fields’ for the first time. What do you mean with this term? Is this the same as ‘sandy deserts’, as referred to in the Introduction. Please define these terms.
Changes: rephrased

Page 7, Line 1. Should read ‘during THE winter season’.
Changes: rephrased

Page 7, Line 12. Use of the word ‘particular’ is not right here.
Changes: rephrased

Page 7, Line 14. ‘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).’ Please expand on this, what conclusions do you draw, do you consider this to be a significant discrepancy, if so why is there a difference?
Changes: we find this a good agreement and now comment on this in the manuscript.

Page 7, Line 26. You refer to emission rates presented by Arnalds et al. (2014). Please provide details as to how these emission rates were determined.
Changes; we added details in the introduction and rephrased this section.

Page 8, Line 12. ‘To understand where dust that is emitted from Iceland can be found in the atmosphere and on the ground’. This sentence is a little clumsy. Could you describe this as ‘to understand the transport of pathways of dust from Icleand..’?
Changes: rephrased

Page 8, Line 29. Typo, remove ‘8’.
Changes: removed

Page 9, Line 3. 'Baddock et al. (2017) did study trajectories from either south or north Iceland and showed that dust from south Iceland....'. Please improve this sentence. I would suggest: 'Baddock et al. (2017) studied the trajectories from sources in both the south and north of Iceland and showed that dust from south Iceland...'.
Changes: rephrased

Page 9, Line 10. Please clarify what you mean here. You state that: 'A large fraction of emitted dust (<20 _m) does not travel far and is deposited in Iceland.' Do you mean that you have found a large fraction of the emitted dust is on particles with diameter <20 um? But I thought you only considered particles up to this diameter? Perhaps you are just reconfirming that you have only considered this size range?
Authors; indeed we wanted to clarify that we only consider dust <20 um.
Changes; we removed (<20 _m)

Page 9, Line 26. 'especially varying' does not make sense. How about: 'deposition varied significantly'. Also, are you referring to deposition rates or where particles were deposited?
Changes: rephrased

Page 10, Line 4. Please correct the sentence: 'In this study we made model simulations'. Incorrect use of the word 'made'.
Changes: rephrased

Page 10, Line 14. Please correct the sentence: 'Best agreement with PM measurements over one year is found close to dust sources.' It does not make sense.
Changes: rephrased

Page 10, Line 21. 'At Storhofdi, 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'. The structure of this sentence needs to be improved. Something along the lines of: '.......the timing of the peaks in dust concentration in our simulations compared well with the observed peaks in measured dust concentrations between 1997 and 2002'.
Changes: rephrased

Page 10, Line 24. Please expand, which way does the dust from the north go?
Changes: rephrased

Page 10, Lines 25 and 26. The use of the term 'much dust', is repetitive and clumsy.
Changes: rephrased

Figures.
Figure 1. Please provide more details on how the soil fractions were determined, where does this data come from? How does soil fraction relate to 'dust' in this context? Is it possible to indicate where the 'dust hotspots' are. Please also improve the colour bar to indicate that 1.0 (?) is the maximum.
Authors; we assigned soil fractions to surface types, the dust hot spots are the locations with maximum bare soil fraction.
Changes; we changed the figure and add a comment in section 2.1

Figures 7 and 8. Please improve the labels on the colour bars. Figure 7b only has two!
And neither 7a, 7b or 8a indicate the maximum value. Also, in my version there are no labels for the individual figures (a and b).
Changes; changed

Temporal and spatial variability of Icelandic dust emissions~~emission~~ and atmospheric transport

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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 PM2.5 and PM10 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. Average annual~~Annual~~ dust emission is~~amounts to~~ 4.3±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 considerable~~much~~ dust amounts are~~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.

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, sand, silt and clay are ~~much dust is~~ deposited in glacio-fluvial plains from where they can be mobilized.~~.~~ 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).

ItModel 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 in Iceland. Analysis of weather observations showed that in the period 1949–2011 on average 16 dust days occurred per year in north-east Iceland and 18 in south Iceland based on synoptic codes for dust observations (e.g. there (Dagsson-Waldhauserova et al., 2014a). In Iceland, not only dust from glacio-fluvial sources or sandur areas can be mobilized, but also tephra (material from volcanic eruptions) is re-suspended frequently and an important dust source (e.g. Arnalds et al., 2016). Dust storms in Iceland are not only frequent, but can transport large amounts of dust. For instance, a 24-hour mean concentration of particulate matter <10 µm (PM10) of 1281 µg m^{-3} was recorded during a dust storm in southern Iceland (Dagsson-Waldhauserova et al., 2015). Arnalds et al. (2013) reported average flux rates of 1440 kg m^{-1} h^{-1} over a 6.5-hour period in an erosion event of volcanic ash.

Impacts of such 2014). Icelandic dust storms are seen inimpact air quality in Reykjavik (e.g. Thorsteinsson et al., 2011), glacier melt rates (e.g. Wittmann et al., 2017) and deposition ofdeposit 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). It is therefore important to know how much dust is transported to these regions or systems. The studies mentioned here so far give valuable information on typical dust events in Iceland, yet partly lack quantitative information and do not consider long-range transport.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 Icelandic dust source regions have been studied (Baddock et al., 2017) and qualitatively describe regions that may be affected. Dust emission amounts from Iceland were estimated by Arnalds et al. (2014). Based on storm frequencies, deposition rates, visibility observations and satellite images they concluded that 30.5 to 40.1 Tg dust is emitted annually in Iceland. Large uncertainties in the extrapolation and conversion of visibility observations to concentration amounts (Dagsson-Waldhauserova et al., 2014a), Model simulations of dust emission in Iceland however, limit the accuracy of this estimate.

Long-term model simulations are lacking. These could greatly improve dust emission estimates and help not only to identify regions possibly affected by Icelandic dust, but would also to allow quantification of dust emissions and transportfor quantitative results in regions where no measurement data are available. Global model simulations with FLEXDUST already indicated that 0.3% of global dust emission may originate from Iceland (Groot Zwaaftink et al., 2016) during a three-year period, but temporal and spatial variability of Icelandic dust emission and transport were not discussed. Detailed modelling of Icelandic dust over a long period will help assess dust emission amounts and identify regions impacted by dust. Even for short events or periods, modelling of erosion is to our knowledge limited to studies of ash resuspension, for example of ash deposited during the Eyjafjallajökull eruption in 2010 and Grimsvotn eruption in 2011 (Leadbetter et al., 2012; Liu et al., 2014; Beckett et al., 2017). These studies showed that timing of ash resuspension events could be represented with relatively simple models assuming fixed threshold friction velocities and accounting for the influence of precipitation. 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 dynamically, but we use a highly detailed surface type map of Iceland (Arnalds, 2015) to identify dust sources. When referring to dust we here include volcanic material that can be remobilized as well as mineral dust, although in our simulations we can only include the sources that are available from the surface type map. After introducing our model, we willto 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 descriptionsdescription

FLEXDUST

FLEXDUST, aA model to estimate for estimates of dust mobilization and emission, FLEXDUST, has been introduced by Groot Zwaaftink et al. (2016). This model estimates dust emission (F) as a function of friction velocity (u_*)),and threshold friction velocity (u_{*t}) and sandblasting efficiency (α), , based on the approach introduced by Marticorena and Bergametti (1995), and originally accounts for snow cover, topography (Ginoux et al., 2001) and described by the following equation,

$$F = c\alpha \frac{\rho u_*^3}{g}\left(1-\frac{u_{*t}^2}{u_*^2}\right)\left(1+\frac{u_{*t}}{u_*}\right) \quad (1)$$

where c is an added constant scaling factor set to $4.8*10^{-4}$, consistent with global simulations presented by Groot Zwaaftink et al. (2016).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). In global FLEXDUST simulations (Groot Zwaaftink et al.,2016) threshold friction velocities are based on sand fraction and a dependency on particle size according to Shao and Lu (2000), soil moisture influences threshold friction velocity according to Fécan et al. (1999), and sediment regions were identified based on large scale topography (Ginoux et al., 2001). For this study on Icelandic dust however, some adaptations were made.

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 surface type map is not changed throughout our model simulations, meaning that changes in dust sources due to for example volcanic eruptions are not accounted for.

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 atheir description of erosion levels (Arnalds et al., 2016) to determine the threshold friction velocity (see Table 1). While Leadbetter et al. (2012) and Liu et al. (2014) chose a fixed threshold friction velocity of 0.4 m s^{-1} for mobilization of volcanic ash, the range of values applied here is more suitable to cover the different conditions of multiple dust sources. Arnalds et al. (2016) give an overview of erosion classes for each surface type. For regions with extremely severe erosion we assume the average of threshold values observed at several sand fields, for severe erosion we assume average conditions of sandy gravel and for considerable erosion we apply an upper threshold observed for sandy gravel (Arnalds et al., 2001). 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), corresponding to the lowest threshold wind velocity estimates for erosion by Arnalds et al. (2016), and a ~~) and~~ slightly larger bare soil fraction (+3%). Bare soil fraction was assigned to dust sources based on surface type, varying between 0.65 and 0.95. A map of the Icelandic bare soil fraction in FLEXDUST is shown in Figure 1. In total, about $16.7 \cdot 10^3$ km^2 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. The combination of the field-based threshold friction velocity and the parameterization of soil moisture effects on threshold friction velocity (Fécan et al., 1999) normally used in FLEXDUST lead to low dust emission rates and ~~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 (see ~~(~~also section 2.3). It therefore appeared that soil moisture processes were wrongly represented by this combination of parameterizations and assumptions. Possible reasons for this are that threshold friction velocities obtained from Arnalds et al. (2001) were not observed during purely dry conditions, the parameterization by Fécan et al. (1999) is not applicable to the studied dust types or that soil moisture of Icelandic dust sources is not represented adequately in the meteorological analysis data we use. Thus, contrary to our previous work (Groot Zwaaftink et al., 2016), soil moisture does not affect threshold friction velocities in this version of FLEXDUST. Alternatively, we use precipitation as an indicator of decreased mobilization. In a model for resuspension of volcanic ash in Iceland, Leadbetter et al. (2012) assumed that precipitation can inhibit mobilization. Based on their model results, they concluded that a time lag before resuming mobilization, that shall represent the time needed to dry the ash after a precipitation event might improve model results. We tested the inclusion of such a time lag, but this did not improve simulation results (see section 3.1.1).~~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. The precipitation threshold is higher than the value of 0.1 mm/h used by Liu et al. (2014). In fact, they found discrepancies between model and observations that indicated that their threshold was set too low or that some time lag for the soil to become wet should be included.

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 a limited extent of dust sources (Arnalds, 2015). Indeed, in~~Furthermore,~~ long-term observations, dust was found on only~~dust frequency showed occurrence of about~~ one ~~dust~~ day in five years in the Westfjords area, and this event~~dust~~ could also have been caused by dust transport~~transported~~ to the Westfjords from the central deserts (Dagsson-Waldhauserova et al., 2014a).

~~2014).~~ Emitted dust is assumed to have a size distribution according to Kok (2011), consistent with previous FLEXDUST simulations. Even though larger particle sizes have been observed in ash remobilization events (e.g. Liu et al., 2014), the Kok (2011) distribution appears more representative for the very fine material found in Icelandic dust sources and dust hot spots (e.g. Dagsson-Walhauserova et al., 2014b; Arnalds et al., 2016).~~).~~ Particles are split in 10 bins of different sizes; the first 5 bins are for particles from 0.2 up to 5 µm~~micrometre~~ diameter, the remaining 5 bins extend up to 20 µm~~micrometres~~.

FLEXPART

FLEXPART~~FLEPXART~~ 10.0 is used to calculate atmospheric transport of emitted dust from Iceland, and has~~as was~~ previously been used to model the transport of~~also done for~~ Saharan dust (Sodemann et al., 2015) and globally emitted dust (Groot Zwaaftink 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 large number~~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). Dry deposition is treated using the resistance method (Stohl et al., 2005), wet deposition distinguishes between liquid-phase and ice-phase 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. The same analysis fields were used in FLEXDUST and FLEXPART simulations. Dust emission was calculated on a 0.01° ~~degree~~ resolution at hourly intervals with FLEXDUST.~~.~~ Emitted particles were gathered in hourly releases at 0.05~~-~~° ~~degrees~~ resolution. These releases were then used as input in FLEXPART simulations. The high resolution of dust emission fields allows us to benefit from the high-resolution surface type maps. Furthermore, initial particle locations are also more accurate, even though meteorological data and topography have a coarser resolution. Notice that this method takes advantage of the Lagrangian nature of FLEXPART which is, in principle, independent of the resolution of the meteorological fields and thus can ingest emission data at any 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, in both FLEXDUST and FLEXPART.~~.~~ For these simulations, dust emissions in FLEXDUST were calculated at 0.02°~~- degrees~~ resolution on a 3-hourly basis and then gathered in 6-hourly releases at 0.5° for FLEXPART. For computational reasons the simulation was split into annual periods, each with an additional spin-up period of one month. ~~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 µmmicrometre (PM10) and smaller than 2.5 µmmicrometre (PM2.5) 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 PM10 and PM2.5, 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

The possibilities for modelModel evaluation areis limited due to a lack of data in Iceland. 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 modelled dust deposited on Vatnajökull and observed deposition in snow samples. They concluded, concluding that the 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 strong 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 PM includeparticulate matter in Iceland included different types of aerosols. Especially for stations near roads like Grensasvegur, concentrations are influenced by traffic emissions of PM. Nevertheless, dust. Dust storms are a recurring cause of episodes with elevated PM10 concentrations exceeding health limits (>50 µg m^{-3}) in Reykjavik

(Thorsteinsson et al., 2011). About 1/3 to 2/3 of the days with PM10 concentration exceeding the health limit in Reykjavik are likely caused by dust storms or by PM from local sources that may be dust as well (Thorsteinsson et al., 2011). Prospero et al. (1995) analysed aerosol samples taken at Stórhöfði in 1991-1993 for NO^{3-}, non sea-salt SO_4^{2-} and methanosulfate and showed that concentrations thereof were similar to values measured in remote ocean regions for about 90 % of the sample set. Peak values in 10% of the sample set were mostly related to aerosol transport from Europe. Moreover, observed nss-SO_4^{2-} concentrations at Irafoss (Reykjavik) and Stórhöfði were comparable during peak events.

The station Raufarfell, however, is located in the vicinity of dust sources and other influences are relatively small. Observed PM10 values (Figure 2) are frequently lower than PM2.5 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 PM2.5 values exceed PM10 values with grey shading in Figures 2 and 3. During these days, observations either underestimate PM10 values or overestimate PM2.5 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^{-3} (Table 2). With the exception of the strongest dust event at the end of the measurement series, modelled concentrations are somewhat overestimating PM10 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^{-3}) is close to the mean observed PM10 concentration (21 µg m^{-3}, Table 2), with almost identical standard deviations, indicating that dust variability is well captured. In Figure 2 we also show PM10 concentrations of a test simulation where we account for a time lag after precipitation in FLEXDUST. Here, we assumed that no dust emission will occur if the sum of precipitation over the last 4 hours exceeds 2 mm, since the sediments or soil need to dry before mobilization is possible. At this station relatively close to dust sources, it becomes clear that with such a time lag, several dust events seen in observations are no longer modelled and the default model is more representative. Probably, the material dries and can be remobilized relatively quickly, thus a drying period does not necessarily need to be accounted for. This is in agreement with observations of dust mobilization in Iceland during intermittent snowfall and wet conditions (Dagsson-Waldhauserova et al., 2014b, Dagsson-Waldhauserova et al., 2015).

All other measurement stations are located near or in Reykjavik and are further awayat larger distance from the dust sources, and closershorter 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 becauseas besides dust emission atmospheric transport and removal processes (and errors in simulating these) 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, PM10 concentrations are overestimated by the model. The results for PM2.5 (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 PM2.5 than PM10 values may indicate that particle size distribution should be shifted, although it could also be due to a larger influence of anthropogenic aerosols on PM2.5 values. As for Hvaleyrarholt, we find that the~~ estimated~~ number of dust storms reaching Reykjavik in fall and early winter is overestimated~~rather too large~~ in the model output. 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. Furthermore, we apply a constant threshold friction velocity that affects both timing and magnitude of modelled dust events. With source depletion and changing weather and soil conditions the threshold friction velocity might vary in time, causing a mismatch of model and observations in particular periods.

High PM10 concentrations in Reykjavik are a cause of concern. A health limit is set at 50 µg m^{-3} 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^{-3} 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 PM10 exceeding 50 µg m^{-3} also appears~~appear~~ overestimated at the other three stations (Table 2). Median values of modelled dust concentrations in Table 2, however, are generally lower than median values of observed PM10 concentrations, as expected since PM10 also includes other aerosol types.

Additionally, we compare weekly mean values of PM10 modelled at high resolution with ECMWF analysis data and at low resolution with ERA Interim data in 2012. The estimated emission in 2012 is 43% lower with ERA interim data (~2.9 Tg) than with hourly ECMWF operational data (~5.1 Tg). Because modelled dust emission has an approximate cubic dependency on friction velocity, higher time and space resolution – which better captures maxima in wind speed and thus friction velocity – can lead to higher emissions. Figure 4 shows that the modelled concentration values during dust events are not always decreased due to a lower resolution. Both episodes with higher and lower concentration values occur. Increases are for instance possible because dust emission grid cells can be larger and thus closer to the stations for the low-resolution simulations. This result thus shows that we cannot assume that a low resolution leads to generally lower concentration values. The results also show that modelled timing of events and order of magnitude of modelled concentrations are mostly maintained at low resolution. However, differences in model results cannot all be purely assigned to model resolution, as there are also other differences present between ERA Interim and ECMWF operational analysis data.

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., 2014a).~~2014). At~~ Stórhöfði is located on the Westman Islands 17 km off the south coast of Iceland (~~,~~ also see Figure 1) and a dust sampler has been operated here for many years (Prospero et al., 2012).~~.~~ 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 Figures 5 and 6.~~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 μg m^{-3} and 10.2 μg m^{-3}, respectively. The root mean squared error between model and observations is 17.6 μg m^{-3}. For the period when sampling was not restricted to wind directions south through west, observed and modelled mean values are 12.7 μg m^{-3} and 11.7 μg 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. Possibly, threshold friction velocity assumptions for specific regions are not valid, the meteorological fields do not capture the actual conditions affecting dust mobilization, or transport modelling is inaccurate due to for example deposition schemes and model resolution. 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 deserts~~fields~~ are the most important dust sources. The long-term averaged emission map (Figure 7~~5~~) identifies important dust sources in NE Iceland and along the south coast and shows a large similarity with bare soil fraction (Figure 1). Differences between bare 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 emission amounts are large~~is emitted~~ according to FLEXDUST because there is less 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, on the other hand, snow cover can inhibit modelled dust emission during the 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 7~~5~~, however, these dust spots are not recognizable as such. Their size is too small (in total approximately 400 km^2 of $16.7 \cdot 10^3$ km^2 ~~-~~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 sandy~~sand~~ field (see e.g. Arnalds et al., 2016 for a description) about 50 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 (2016)~~,~~ 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 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 including minor events (Dagsson-Waldhauserova et al., 2014a). Given the dependency of this observation on the number and location of observations this is a good agreement. Days with largest dust emission occur in winter/early spring according to FLEXDUST. ~~(Dagsson-Waldhauserova et al., 2014).~~

3.2.2 Interannual variability

The average annual~~Annual~~ mean dust emission in the period 1990 until 2016 is~~amounts to~~ 4.3±0.8 Tg. This is similar to the FLEXDUST~~FLEXUDST~~ estimate for dust emission in Iceland in years 2010 through 2012 in global simulations (4.8 Tg, Groot Zwaaftink 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 maxima in wind speed - lead to systematically higher emissions.~~ Dust emission rates are an order of magnitude lower than previous estimates of dust emission rates (30.5 to 40.1 Tg annually) 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 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, unless the extra mass would be attributed almost exclusively to larger particles that never reach the measurement stations.

The North Atlantic Oscillation (NAO) is an important mode of meteorological variability in the North Atlantic and Europe (Hurrell et al., 2013). According to Polar MM5 simulations by Bromwich et al. (2005), changes in the NAO modulation of regional climate influence precipitation patterns in Iceland through shifts in the Icelandic low. To analyse~~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 8~~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 °N) and north Iceland (see Figure 8~~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.

3.3 Aeolian transport and dust deposition

To understand the transport of pathways of~~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 9~~7~~), as large fractions~~much~~ of the emitted dust are~~is~~ deposited after only short~~small~~ travel distances (Figure 10). Dust concentrations rapidly decrease with altitude; 40% of suspended dust is on average situated at altitudes below 1000 m above ground level and only 6 % at altitudes above 5000 m (not shown). This is consistent with the discussion on altitude distribution of high-latitude dust presented in Groot Zwaaftink et al. (2016~~8~~).

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 8~~6~~) and the main wind direction during dust storms in north east Iceland is from the south (Dagsson-Waldhauserova et al., 2014a), the majority of~~2014), much~~ dust appears to be transported northwards. But also dust deposition south of 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 11a~~9a~~ correlation between annual dust emission and annual deposition at each point is 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 significantly~~much~~ here, only dust amounts. Given this large correlation, we have normalized dust deposition to annual dust emission for further analyses in Figure 11b~~9b~~ and 11c~~9c~~. Correlations between dust emission in north-east Iceland and normalized deposition (Figure 11b~~9b~~) show a similar ~~8~~ (yet weaker) pattern as Figure 11a~~9a~~. Focussing on dust emission in south Iceland (Figure 11c~~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 co-occurring with emissions in the south.~~.~~ The strong correlation between dust emission in north and south Iceland (r^2=0.67, also see Figure 8~~6~~) means that we cannot properly separate influences of these two source regions on dust deposition in specific regions. Baddock et al. (2017) studied the~~did study~~ trajectories from sources in both the~~either~~ south and~~or~~ north of Iceland separately 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, as transport pathways might be influenced by NAO.~~.~~ Transport of air pollution from Europe to the Arctic for instance is strongly linked to NAO (Eckhardt et al., 2003). However, Figure 11d~~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 µm)~~ does not travel far and is deposited in Iceland. This fraction is~~amounts to~~ 1.5 ± 0.3 Tg (Figure 12~~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 Tg(~5%) or on average 16 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 Tg or 58% of annually emitted dust. This estimate is much lower than the 14 Tg estimated by Arnalds et al. (2014), consistent with lower FLEXDUST emission rates. Smaller~~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 amounts strongly varied~~was especially varying~~ in the first years of our simulation period. From Figure 10~~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 g m^{-2} yr^{-1}. On average however, dust deposition in Greenland is only about 0.04 g m^{-2}. Especially in north-west Greenland, Icelandic dust deposition amounts are low, with for instance mean deposition amounts of less than $5 \cdot 10^{-3}$ g m^{-2} yr^{-1} at NEEM Camp (77.45°N, 51.06°W). Most Icelandic dust stays in the near Arctic (>60°N), where on average about 78% of dust is deposited. However, only about 7% of emitted dust is deposited in the high Arctic (>80°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 studied ~~made model simulations of~~ dust emission and transport from Iceland over a period of more than two decades through model simulations.~~.~~ 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 is~~amounts to~~ 4.3±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 22.000km^2, Arnalds et al., 2016) are approximately 0.2 kg m^{-2} yr^{-1} and are comparable to estimated dust emissions in the western Sahara (0.1 kg m^{-2} 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. It is thus hard to fully constrain dust emission estimates. We ~~Best agreement with PM measurements over one year is~~ found better agreements between modelled and observed PM concentrations close to dust sources than far away from 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 PM10 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. Also other dust sources may be depleted or get covered, for instance by lava, and require adjustment of the surface type map currently not implemented. Furthermore, assumptions on the threshold friction velocity influence timing and magnitude of modelled dust events and may be less representative in specific periods as threshold friction velocity changes with surface conditions. Additionally, model evaluation based on PM observations is complicated by the inclusion of aerosol types other than dust, especially in domestic areas and near the coast.~~.~~ At Stórhöfði, near the south coast of Iceland, the timing of the peaks in dust concentration~~concentrations is very well captured~~ in our simulations compared well with the observed peaks in ~~, 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 and directed north-eastwards, in south Iceland they are more variable. Emitted dust can travel over long distances, reaching Europe (3% of emitted dust) or Svalbard (0.1%). A large fraction of emitted~~Much~~ dust, especially large particles, is deposited close to dust sources and therefore stays in Iceland (34%). Dust deposition on Icelandic glaciers is~~Glaciers in Iceland~~ thus substantial, ~~receive much dust (~~annually about 16 g m^{-2}, although this value is dependent on model resolution, due to the close proximity of dust sources and glaciers..~~).~~ 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. ~~Similarly, annually about 2% of Icelandic dust is deposited in Greenland, mostly at lower altitudes.~~

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. Further research is also needed to better understand the dynamic changes in dust source regions due to volcanic eruptions. Re-suspension of volcanic ash is currently often treated separately from dust mobilization (e.g. Leadbetter et al., 2012; Liu et al., 2014; Beckett et al., 2017), although both processes are closely related and treatment of these sources should be unified.

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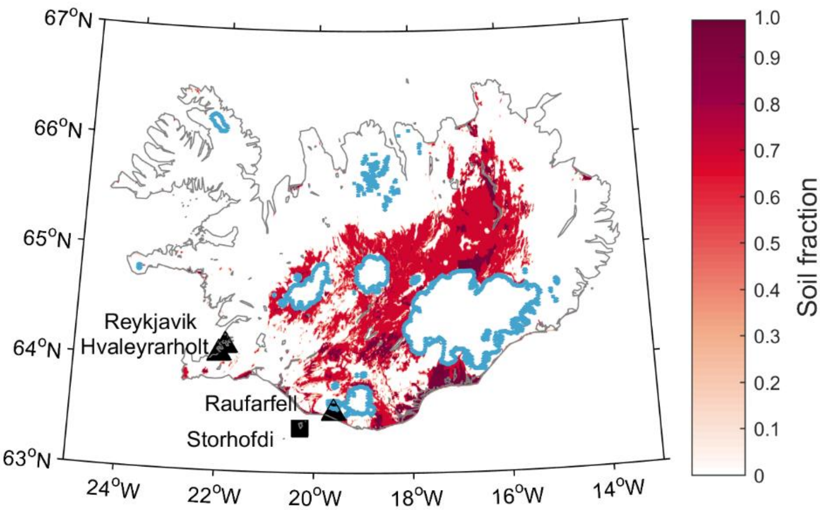
Table 1 Threshold friction velocity based on observations presented by Arnalds et al. (2001) in each erosion class described by Arnalds et al. (2016).

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

Table 2 Statistics on observed PM10 concentrations (µg m^{-3}) and simulated dust (d<10 µm) concentrations (µg 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 µg	13	31	3	17	7	16	3	14



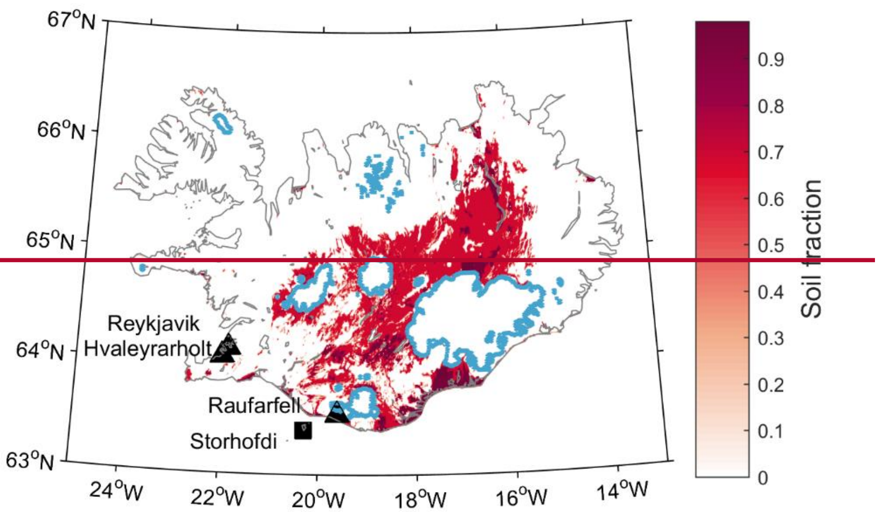
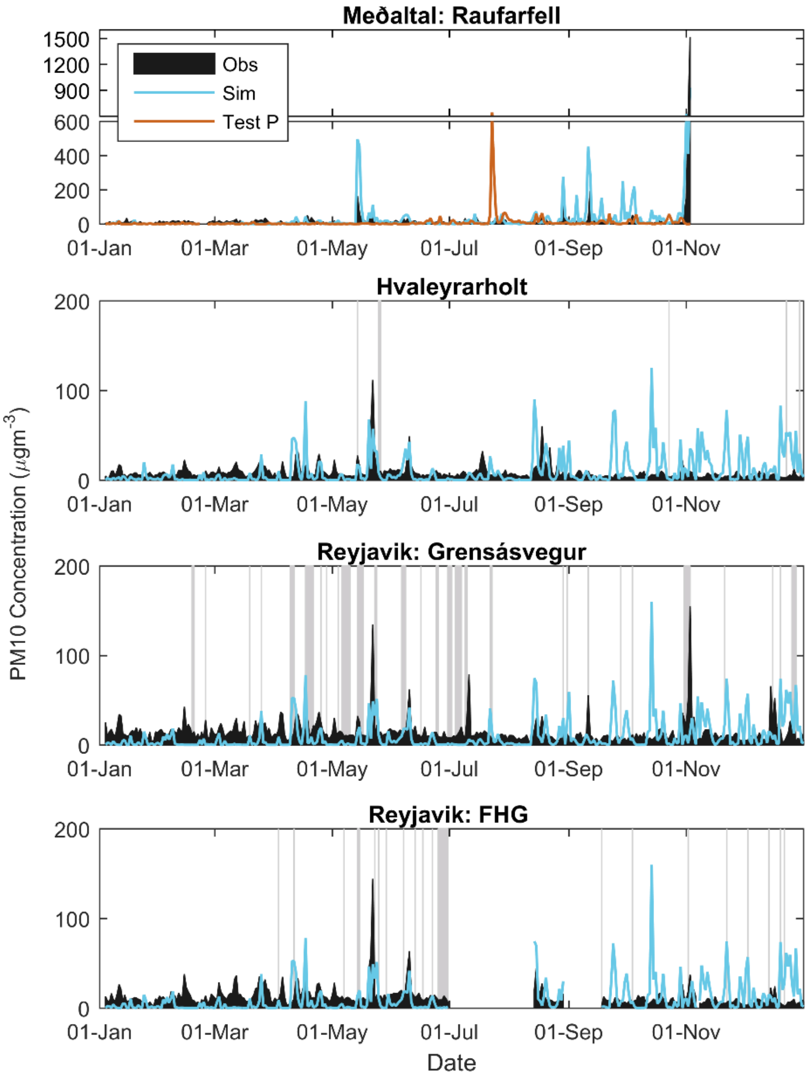


Figure 1 Aeolian active bare soil fraction as assumed in FLEXDUST. The triangles indicate stations with PM measurements. The square marks the Storhofdi station with dust concentration measurements. The blue lines are glacier outlines.


Meðaltal: Raufarfell
Obs
Sim
Test P
1500
1200
900
600
400
200
0
01-Jan
01-Mar
01-May
01-Jul
01-Sep
01-Nov
Hvaleyrarholt
200
100
0
Reyjavik: Grensásvegur
Reyjavik: FHG
PM10 Concentration (μgm^{-3})
Date

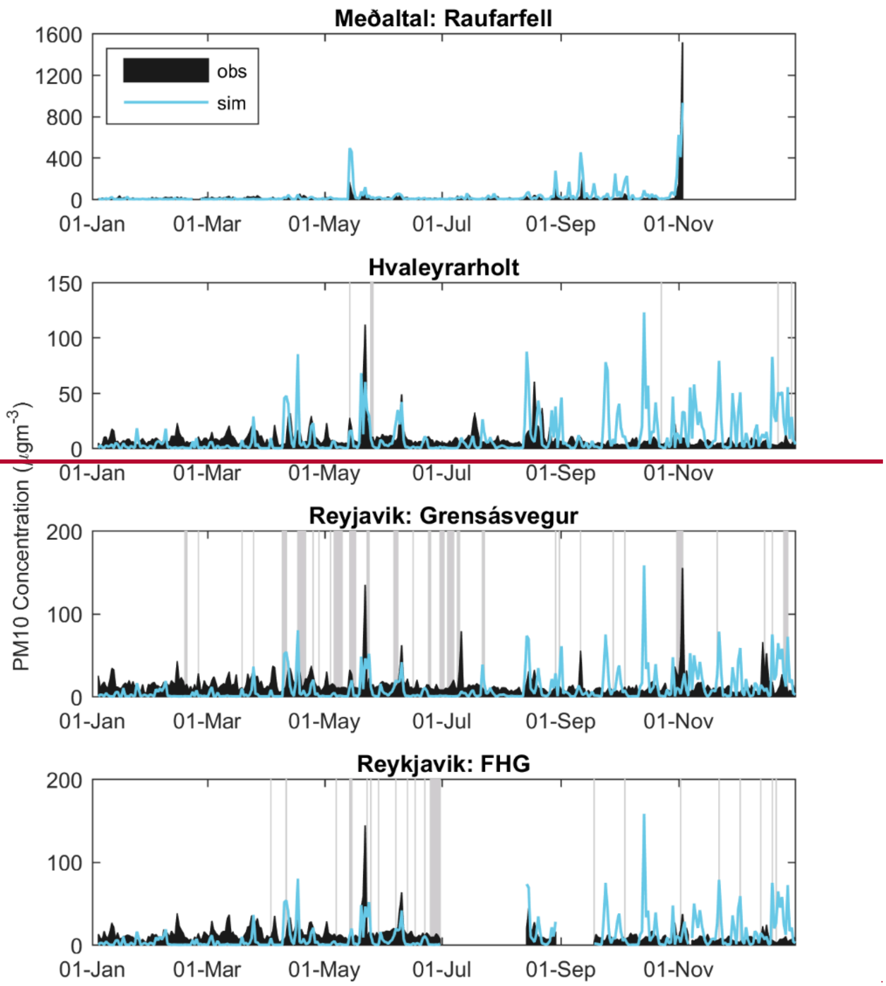


Figure 2 Daily mean PM10 concentrations (µg m^{-3}) as observed (black) and modelled (blue) in 2012. A simulation where a time lag after precipitation was taken into account is shown in red at Raufarfell. Shaded grey areas indicate periods with inconsistent measurements of PM10 and PM2.5 (also see figure 3).

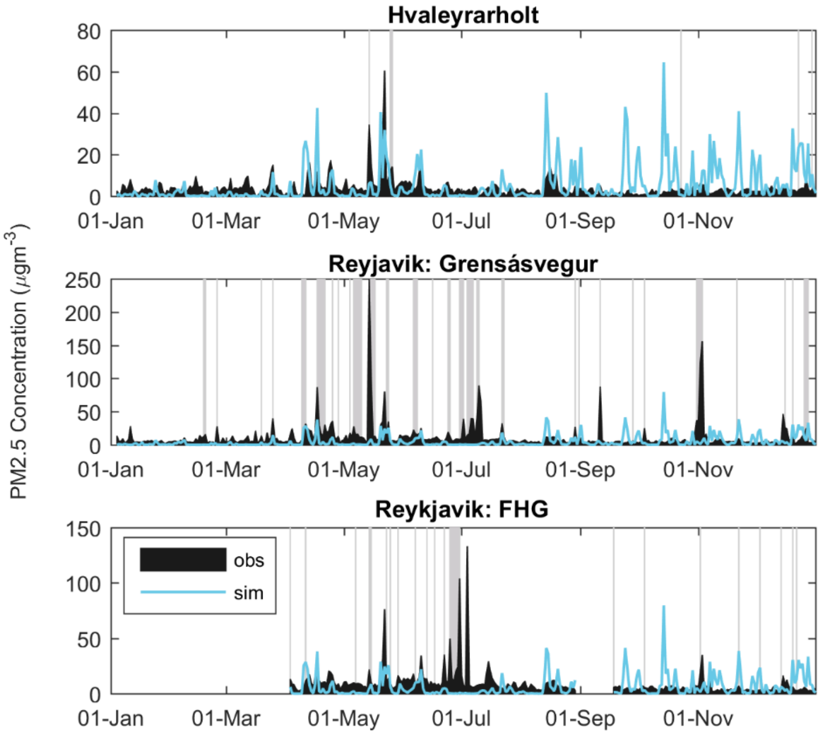


Figure 3 Daily mean PM2.5 concentrations (µg m^{-3}) as observed (black) and modelled (blue) in 2012. Shaded grey areas indicate periods with inconsistent measurements of PM10 and PM2.5 (also see figure 2).

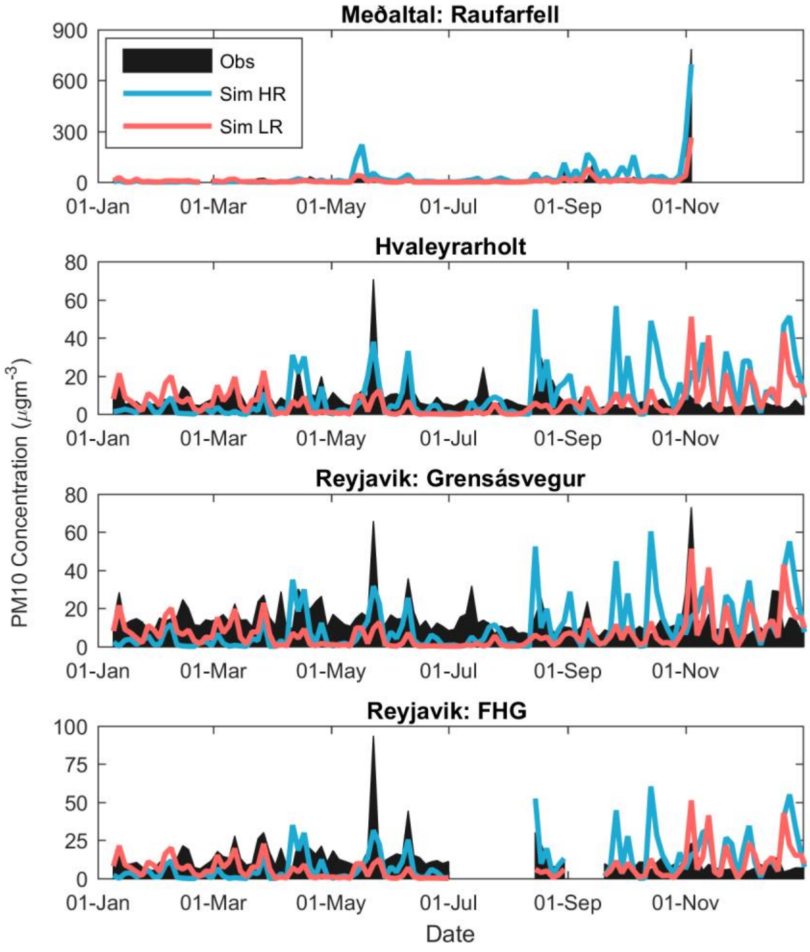


Figure 4 Weekly mean PM10 concentrations at four stations as observed (black), modelled at high resolution (blue) with ECMWF analysis data (0.2°) and modelled at low resolution (with ERA Interim data (1.0°, red).

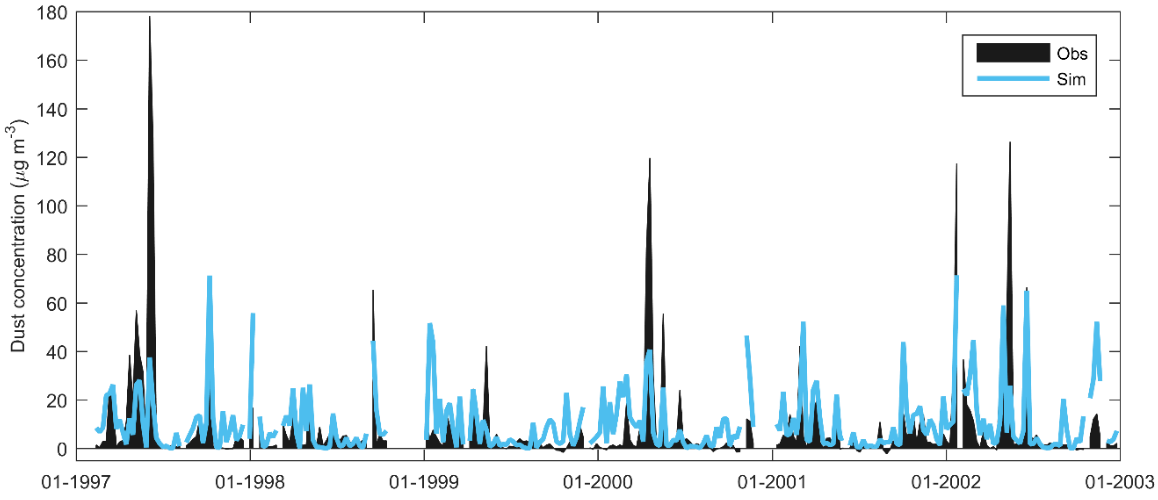
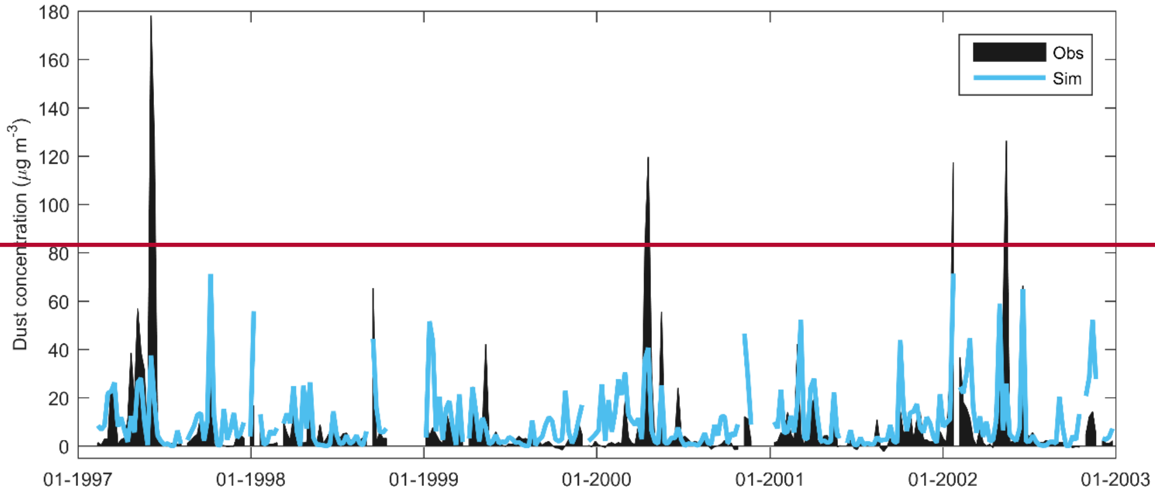


Figure 5



~~Figure 4~~ **Observed (black) and modelled (blue) weekly mean dust concentration (μg m-3) at Stórhöfði /Heimaey.**

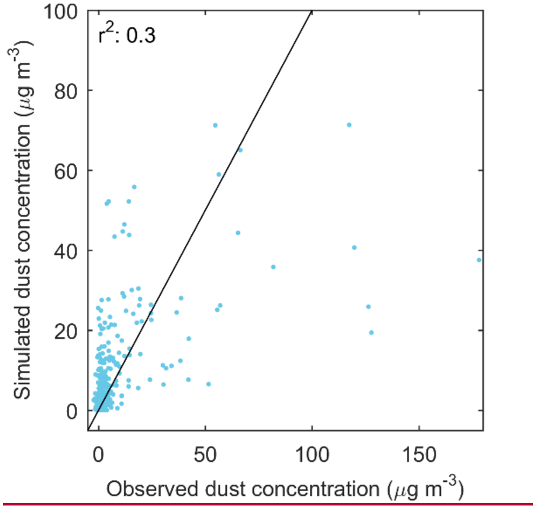


Figure 6 Weekly mean simulated versus observed dust concentration (μg m^{-3}) at Stórhöfði /Heimaey. The black line shows where simulated and observed values are identical.

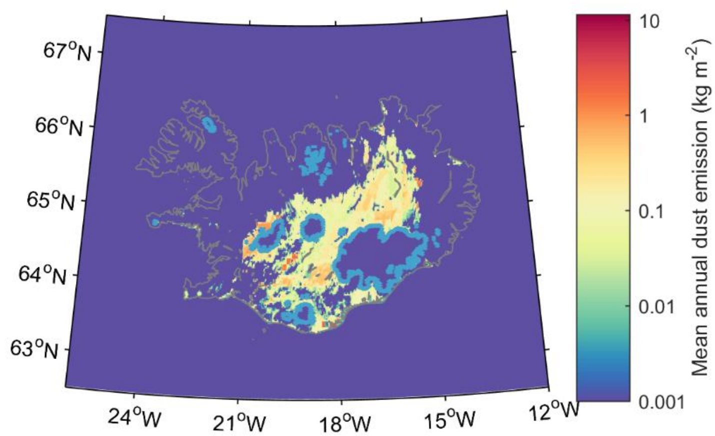


Figure 7~~5~~ Simulated annual mean dust emission (kg m^{-2}) in years 1990-2016

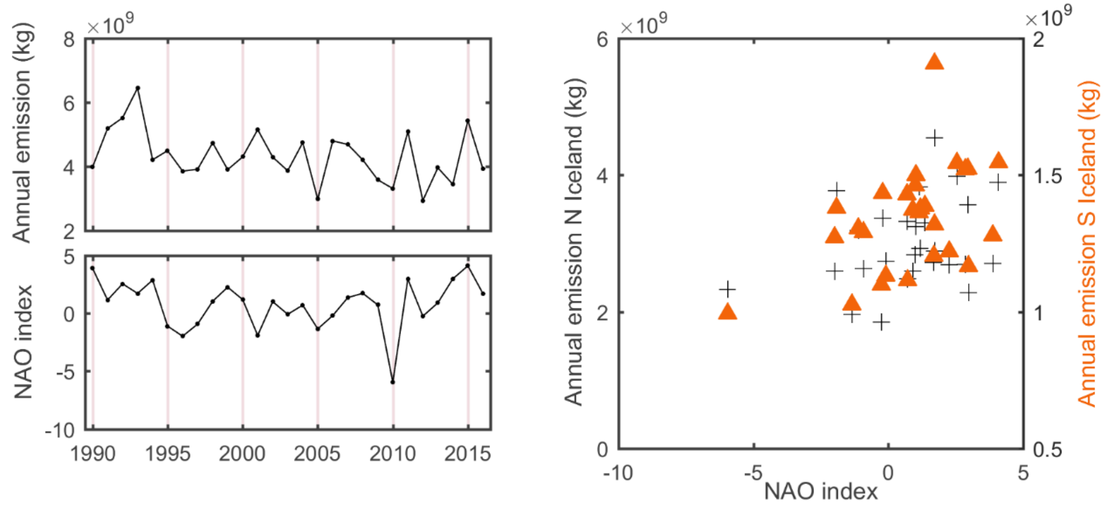
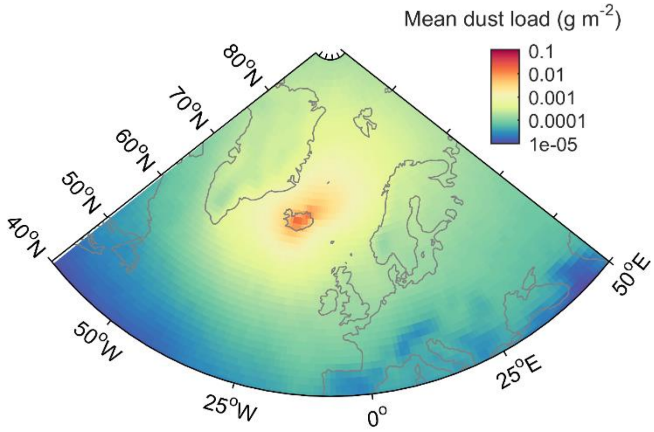
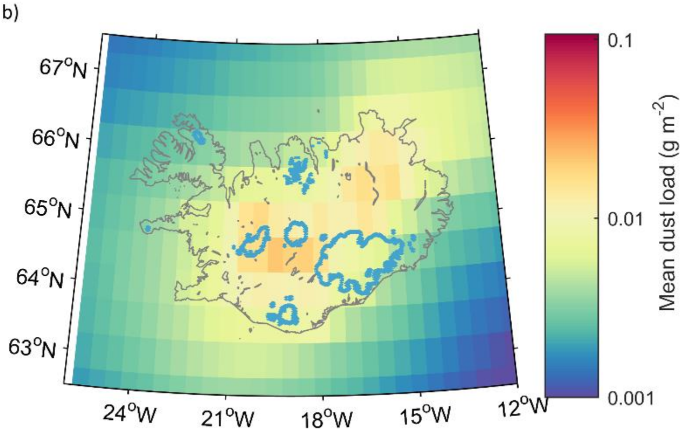


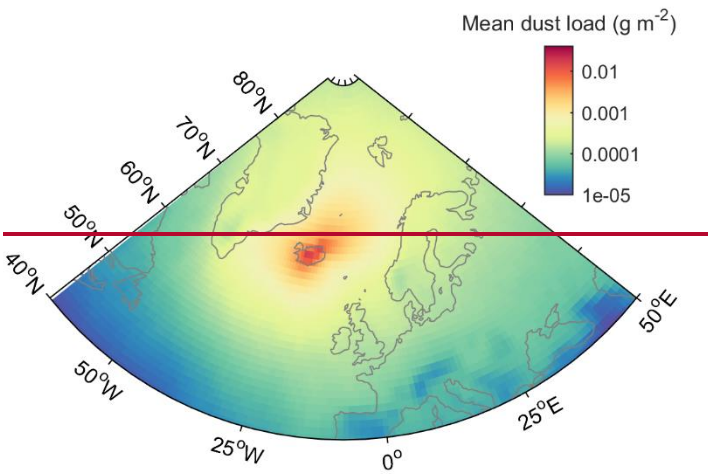
Figure 86 Left: Annual dust emission from Iceland in years 1990 until 2016 (top) and the annual NAO index (bottom). Right: Annual emission from Northern Iceland (>64.3˚N3 degr. N) and southern Iceland (<64.3 °degr. N) versus annual NAO index.

a)


Mean dust load (g m^{-2})
0.1
0.01
0.001
0.0001
1e-05
80°N
70°N
60°N
50°N
40°N
50°E
50°W
25°W
0°
25°E

b)


67°N
66°N
65°N
64°N
63°N
24°W
21°W
18°W
15°W
12°W
0.1
0.01
0.001
Mean dust load (g m^{-2})


Mean dust load (g m^{-2})
0.01
0.001
0.0001
1e-05
80°N
70°N
60°N
50°N
40°N
50°E
50°W
25°W
0°
25°E

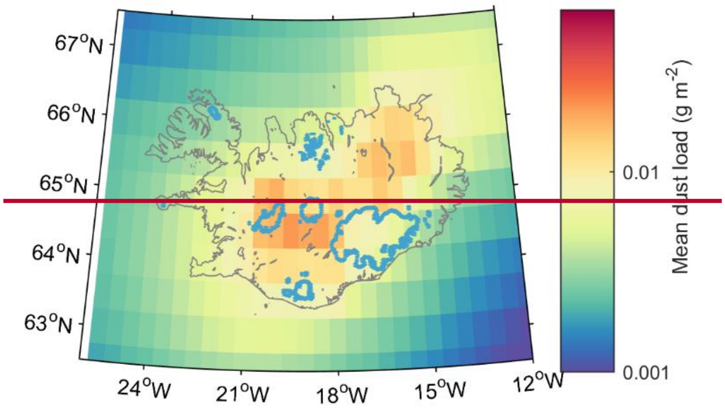
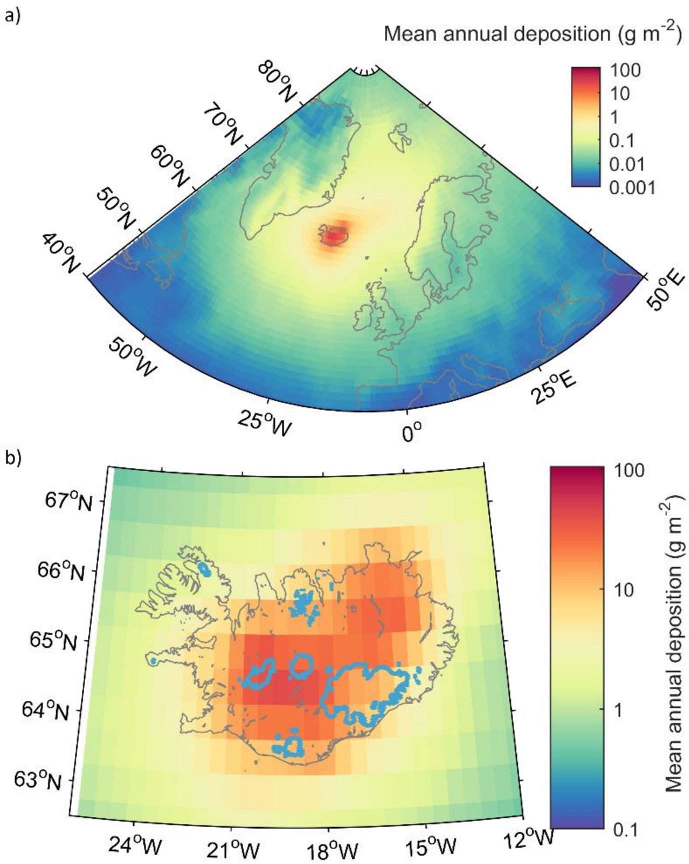
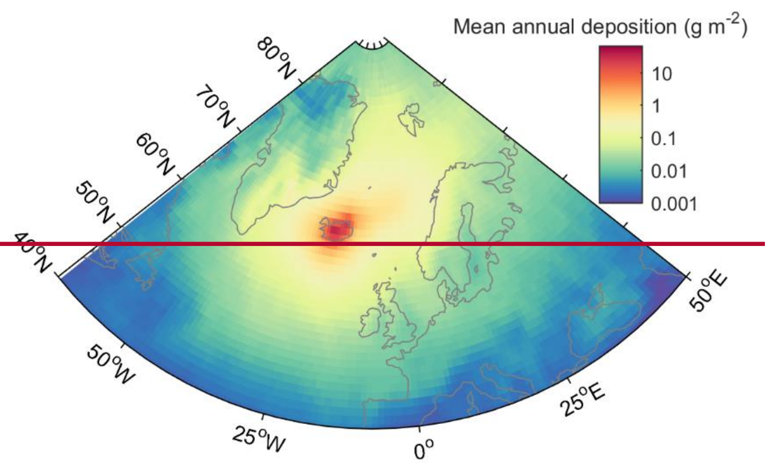


Figure ~~7~~9 Mean atmospheric dust load (g m^{-2}) simulated with FLEXPART in years 1990-2016 for the North Atlantic region (top) and Iceland (bottom). The blue lines in the bottom figure are glacier outlines.


a)
Mean annual deposition (g m-2)
100
10
1
0.1
0.01
0.001
80°N
70°N
60°N
50°N
40°N
50°E
50°W
25°W
0°
25°E
b)
67°N
66°N
65°N
64°N
63°N
24°W
21°W
18°W
15°W
12°W
100
10
1
0.1
Mean annual deposition (g m-2)


Mean annual deposition (g m-2)
10
1
0.1
0.01
0.001
80°N
70°N
60°N
50°N
40°N
50°E
50°W
25°W
0°
25°E

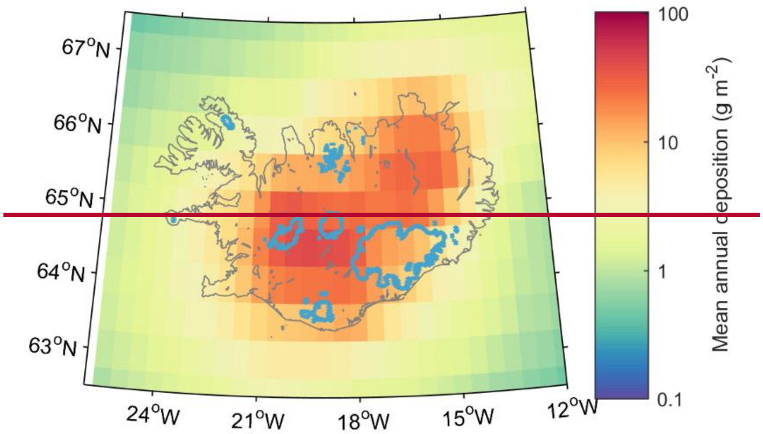


Figure 10~~8~~ Mean annual dust deposition (g m^{-2}) simulated with FLEXPART in years 1990-2016 for the North Atlantic region (top) and Iceland (bottom). Maximum values are lower in the upper panel than in the lower panel as this figure shows averages over larger areas. The blue lines in the bottom figure are glacier outlines.

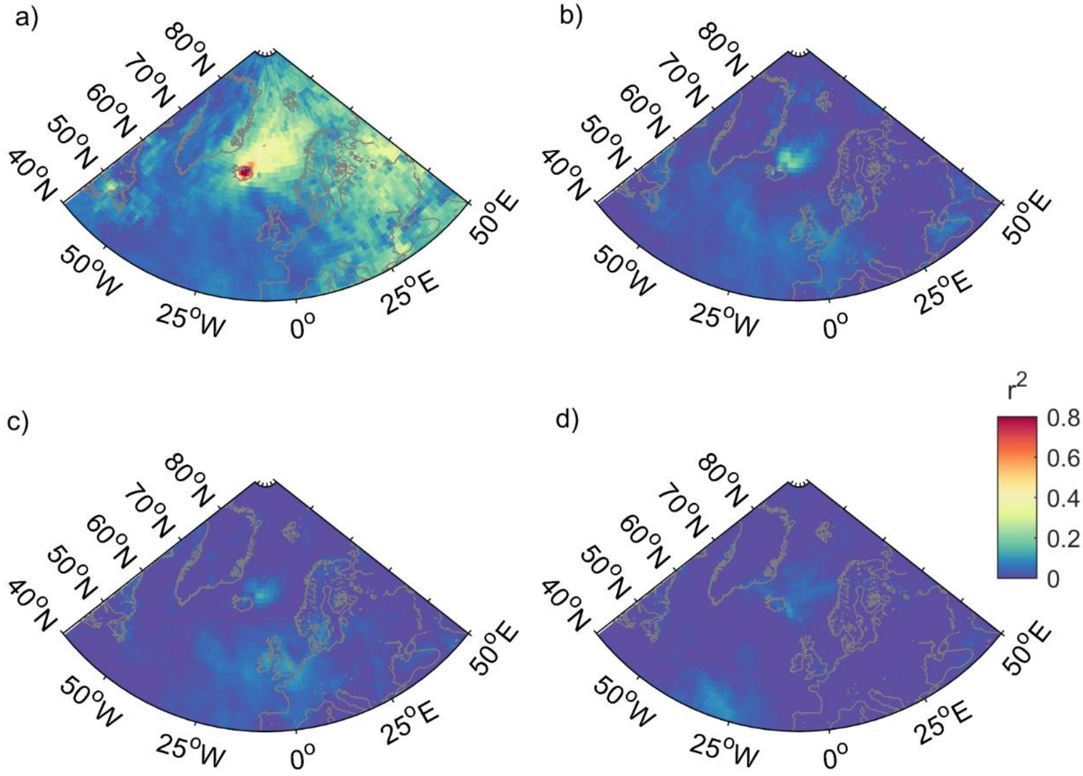


Figure 119 Coefficient of determination r^2 for monthly time series of dust deposition and emission (a), dust deposition normalized by total emission and emission in N Iceland (b), dust deposition normalized by total emission and emission in S Iceland (c), dust deposition and the NAO index (d).

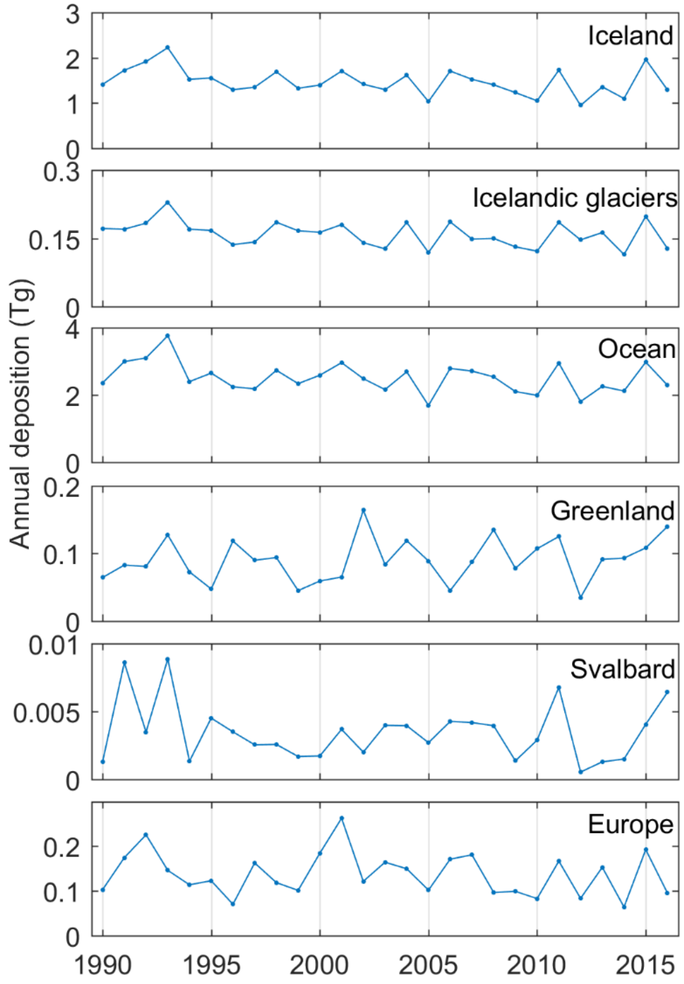


Figure ~~1210~~ Time series (1990-2016) of modelled dust deposition (Tg y^{-1}) in specific regions. Note that Iceland also includes deposition on Icelandic glaciers.