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A model study of the pollution effects of the first three months of the Holuhraun volcanic fissure

B. M. Steensen[1] and M. Schulz[1] and N. Theys[2] and H. Fagerli[1]

[1]{Norwegian Meteorological Institute, Postbox 43 Blindern, 0313 Oslo, Norway }

[2]{Belgian Institute for Space Aeronomy, Ringlaan-3-Avenue Circulaire, B-1180 Brussels, Belgium }

Correspondence to: B. M. Steensen (birthems@met.no)

Abstract

The volcanic fissure at Holuhraun, Iceland started at the end of August 2014 and continued for six months to the end of February 2015. Lava floated onto the Holuhraun plain associated with large SO_2 emissions. In this paper we present results from EMEP/MSC-W model simulations where we added 750 kg/s SO_2 emissions at the Holuhraun plain from September to November. The emission amounted to approximately 4.5 times the daily anthropogenic SO_2 emitted from the 28 European Union countries, Norway, Switzerland and Iceland. Model results are compared to satellite observations and European surface measurements. The dispersion but also the ambiguity of the satellite data, due to what is assumed in the retrieval as a priori SO_2 profile, is further explored with model sensitivity runs using different emission height distributions from the volcano. Satellite-comparable adjusted model vertical column densities are calculated for the different sensitivity runs where the SO_2 mixing ratios from different vertical layers are weighted with the averaging kernel. The results show the importance of using the averaging kernel when comparing the model to satellite column loads, the maximum column densities over 10 DU in the original model data are reduced by around 50 % due to the weighting. For most days the satellite retrievals have higher mass burdens values than the adjusted model when summed up over the North Atlantic area. The discrepancies are explained by the unrealistic constant emission term in the model simulations, and because the area used for the summation is dependent on the satellite data detection limit, and the correct position of the model SO_2 plume. Surface observations in

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Europe showed peak type increases of SO_2 concentrations from volcanic plumes passing by and lasting only for a short time. Three well identified episodes are documented for more detail. For all the events the timing of the observed concentration peaks compared to the model quite well. For the first episode presented, the model concentrations are only about 10% to 40% of the observed concentrations. The transport of SO_2 to Europe during this event is found to contribute to very high measured and modelled concentrations at the stations. For the later plumes, the observed and model concentrations at the stations compare better in magnitude. The overall changes in the European SO_2 budget due to the volcanic fissure are estimated. SO_X three monthly wet deposition in the 28 European Union countries, Norway and Switzerland is found to be more than 30 % higher in the control model simulation with Holuhraun emission compared to a model simulation with no Holuhraun emission. The biggest increases, apart from Iceland, are found on the coast of Northern Norway, a region with frequent precipitation during westerly winds. The total deposition levels in this region become equal to the most polluted regions over Europe and the average model deposition for Norway is doubled the level it was back in 1990. For SO_2 and $PM_{2.5}$ concentrations, there is only a ten and six percent increase over Europe between the two model simulations, respectively. Although the percent increase of $PM_{2.5}$ concentration is highest over Scandinavia and Scotland, an increase in PM exceedance days is found over Ireland and the Benelux region. Especially the Benelux region is already very polluted, so that a small increase in pollution leads to an increase in exceedances days. Although there was a large increase in total daily emission of SO_2 over Europe due to the eruption, Iceland is located too far away to make a large impact on average pollution levels in the European countries, except in Iceland itself.

1 Introduction

Increased seismic activity in the Bárðarbunga volcano was recorded by the Icelandic Met Office from the middle of August 2014 (http://en.vedur.is/earthquakes-and-volcanism/volcanic-eruptions/holuhraun/). The activity continued in the volcano but some tremors appeared also towards the Holuhraun plain, a large lava field north of the Vatnajökull ice cap, the latter covering the Bárðarbunga and Grimsvötn volcano. On August 31 a continuous eruption started at Holuhraun with large amounts of lava pouring onto the plain and large amounts of sulphur dioxide (SO_2) emitted into the atmosphere (Sigmundsson et al.

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2015). Thordarson and Hartley (2015) estimated SO_2 emissions from the magma at Holuhraun to be around 30 kt/d to 120 kt/d over the first three months of the eruption, with a maximum during the first two weeks of September. Schmidt et al. (2015) also found that among several model simulations with different emission fluxes, the model simulations with the largest emission (120 kt/d) compared best with satellite observations at the beginning of September. In comparison, Kuenen et al. (2009) estimated the daily anthropogenic emission from the 28 European Union countries for 2009 to be 13.9 kt/d, while the 2013 estimate is 9.8 kt/d (EMEP, 2015). The eruption ended in February 2015 and during the 6 months of eruption a total of approximately 11 (± 5) Tg SO_2 may have been released (Gislason et al. 2015). It is of interest to investigate the impact of these volcanic emissions on current SO_2 levels in Europe. In the last decades, measures have been taken to reduce SO_2 emissions, triggered by the Convention on Long-range Transboundary Air Pollution (LRTAP), in Europe. Significant reductions of 75% in emission between 1980 and 2010 are confirmed by observations (Torseth et al., 2012). The impact of volcanic eruptions with SO_2 emissions can thus perturb the European atmospheric sulphur budget to a larger extent than before and potentially lead to new acidification of lakes and soils if the eruption would last over a long time period.

For comparison, the big 1783 Icelandic Laki eruption lasted eight months and released a total amount of estimated 120 Tg of SO_2 over eight months. The resulting sulphuric acid caused a haze observed in many countries of the northern hemisphere and increased mortality in Northern Europe (Grattan et al., 2003, Thordarson and Self, 2003, Schmidt et al., 2011). The fissure at Holuhraun was much weaker than the Laki fissure, both in terms of amount of SO_2 released and probably also the height of the eruptive column. Thordarson and Self (1993) estimated that the Laki erupted at emission heights up to 15 km, while the observations of the Holuhraun eruptive cloud saw the plume rising up to 4.5 km (vedur.is). Ground level concentrations exceeded the Icelandic hourly average health limit of 350 µg/m^3 over large parts of Iceland (Gislason et al. 2015). The World Health Organization (WHO) has a 10 minute limit of 500 µg/m^3 and a 24-hour limit of 20 µg/m^3. High hourly mean surface concentrations of SO_2 were measured in Ireland (524.2 µg/m^3), but then also in Austria (247.0 µg/m^3) and Finland (180 µg/m^3) (Schmidt et al. 2015, Ialango et al. 2015).

A climate impact of high SO_2 emissions may be suspected, such as a cooling of climate due to an increase in aerosol loadings. Gettelman et al. (2015) using a global climate model found a small increase in cloud albedo due to the Holuhraun emissions resulting in -0.21 Wm^{-2}

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difference in radiative flux on the top of the atmosphere. If the event had happened earlier in the summer a larger radiative effect could be expected (-7.4 Wm^{-2}). Understanding the atmospheric sulphur budget associated to such events is thus of great interest also for climate science. The Holuhraun eruption can also serve as a prototype to study ash transport from an Icelandic volcano. Unlike the two previous big eruptions in Iceland, Eyjafjallajökull in 2010 and Grímsvötn in 2011, this eruption did not emit ash that disrupted air traffic. However, uncertainties in source estimates, time varying emissions from a point source, dependence of transport on initial injection height, transport and removal processes from Iceland to Europe are similar problems for SO_2 and ash plumes. Despite Moxnes et al. (2014) showing that SO_2 and ash can have different eruption heights, proven capability of modelling the transport of a SO_2 plume can be useful for judging future eruption scenarios where ash can cause a problem.

This study will focus on simulated air quality effects and the perturbed sulphur budget due to the volcanic SO_2 emissions during the first three months, the first two covered also by satellite observations. Several stations in Europe reported high concentrations of SO_2 during this time and case studies are chosen to evaluate simulated plume development over Europe. The transport is modelled with the EMEP/MSC-W chemical transport model, one of the important models used for air quality policy support in Europe during the last 30 years (Simpson et al. 2012). Both station and satellite data are compared to model results to understand the amplitude and magnitude of the sulphur budget perturbation. A big uncertainty for any volcanic eruption modelling is the emission term, both with respect to height and magnitude of the plume. The impact of the height distribution of the emissions is studied through sensitivity simulations. Finally the perturbed European sulphur budget, as simulated by the EMEP/MSC-W model, is documented and discussed.

2 Methods

2.1 Model description

The model simulations of the transport of the SO_2 Holuhraun emissions are done with the 3-D Eulerian chemical transport model developed at the Meteorological Synthesizing Centre-West (MSC-W) for the European Monitoring and Evaluation Programme (EMEP). The EMEP/MSC-W model is described in Simpson et al. (2012). Sulphate production from SO_2 in both gas phase and aqueous phase are accounted for. The dry deposition in the model is

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parameterized for different land types. Both in-cloud and sub-cloud scavenging are considered for wet deposition.

The simulations use the EMEP-MACC (Monitoring Atmospheric Composition and Climate) model configuration. The horizontal resolution of the model simulations is 0.25^o (longitude) x 0.125^o (latitude). There are 20 vertical layers up to about 100 hPa, with the lowest layer around 90 meters thick. The model is driven by meteorology from the European Centre of Medium-Range Weather Forecasts (ECMWF) in the MACC model domain (30^o west to 45^o east and 30^o to 76^o north). Iceland is in the upper northwestern corner of the domain, which implies losses of sulphur from the regional budget terms in sustained southerly and easterly flow regimes. The meteorology fields used have been accumulated in the course of running the MACC regional model ensemble forecast of chemical weather over Europe (http://macc-raq-op.meteo.fr), of which the EMEP/MSC-W model is part of. For our hindcast type simulations here, only the fields from the first day of each forecast are used. The meteorology is available with a three hourly interval. All model simulations are run from September through November 2014.

Emission from the Holuhraun fissure is set to a constant 750 kg/s SO_2 (65 kt/d) for the entire simulation. For all model runs the anthropogenic emissions are as standard for our EMEP MACC model configuration. Table 1 shows an overview of the four different model runs that are used in this study. For the control run called ctrl_hol, volcanic emissions at Holuhraun are distributed equally from the ground up to a 3 km emission column height. To test the sensitivity towards emission height, two additional model simulations are done, low_hol and high_hol. To derive the impact purely due to the emissions from Holuhraun, a simulation with no Holuhraun fissure emissions is used, called no_hol.

Anthropogenic SO_2 emissions in the model are described in Kuenen et al. (2014). There is a yearly total SO_2 emission of 13.2 Tg/a corresponding to 2009 conditions, the same year that is used in the reference MACC model configuration. The difference to actual 2014 conditions is assumed to be unimportant here. The inventory includes 2.34 Tg/a SO_2 in yearly ship emissions over the oceans. Over the continents the yearly emissions are 5.08 Tg/a SO_2 for the 28 EU countries, and 5.53 Tg/a SO_2 for the non-EU countries in the MACC domain (including Iceland) covered by the MACC domain.

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2.2 Observations

The satellite data used in this study stem from the Ozone Monitoring Instrument (OMI) aboard NASA AURA (Levelt et al., 2006). The satellite was launched in July 2004 as part of the A-train earth observing satellite configuration and follows a sun-synchronous polar orbit. The OMI measures backscattered sunlight from the Earth atmosphere with a spectrometer covering UV and visible wavelength ranges. Measurements are therefore only available during daytime. The background SO_2 concentrations are often too low to be observable, but increases in SO_2 from volcanic eruptions can produce well distinguishable absorption effects (Brenot et al. 2014). Pixel size varies between 13 km x 24 km at nadir and 13 km x 128 km at the edge of the swath. OMI satellite data are affected by "row anomalies" due to a blockage affecting the nadir viewing part of the sensor, which affects particular viewing angles and reduces the data coverage. The zoom-mode of OMI reduces the coverage on some days. The coverage is also reduced by missing daylight, e.g. winter observations from high latitudes are absent. Therefore data from only the two first months from September until the end of October are used in this study.

The retrievals are described in Theys et al. (2015). The sensitivity of backscatter radiation to SO_2 molecules varies with altitude (generally decreasing towards the ground level) and therefore the algorithms use an assumed height distribution for estimating the integrated SO_2 column density. Since often little information is available at the time of eruption and the retrievals produce results daily (even for days with no eruption) an assumed a priori profile is used for the vertical SO_2 distribution. The satellite retrievals used here assume an a priori profile with a plume thickness of 1 km that is centred at 7 km, similar to the method described in Yang et al. (2007). This may be too high for the Bardarbunga eruption, since our simulations indicate that the plume was often situated much lower in the troposphere. Retrieved SO_2 column densities may thus be too low. To compare the vertical column density (VCD) from the model to the one from satellite retrievals, the averaging kernel from the satellite has to be used. Each element of an averaging kernel vector defines the relative weight of the true partial column value in a given layer to the retrieved vertical column (Rodgers 2000). Cloud cover also changes the averaging kernel and a spatio-temporally changing kernel is part of the satellite data product (an averaging kernel is provided for each satellite pixel).

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To apply the averaging kernel on model data, the satellite data are regridded to the model grid so that those data from satellite pixels nearest to any given model grid point are used for that grid point. A smaller area than the whole model domain was chosen to study and compare to the satellite data, 30^o west to 15^o east and 45^o to 70^o north (red boxes in Figure 1). The Aura satellite does five overpasses over the domain during daytime, swaths are partly overlapping in the northern regions. For the grid cells where the swaths overlap, the satellite observations are averaged to produce daily average fields. There are also regions that are not covered by satellite observation that will not be taken into account in the model data postprocessing. To make comparable daily averages of the model data, the closest hour in the hourly model output are matched to the satellite swath time and only grid points that are covered by satellite are used. The profiles for the averaging kernel in the satellite product are given on 60 levels, the values from these levels are interpolated to model vertical levels. The new adjusted model VCD is then calculated by multiplying the interpolated averaging kernel weights to the SO_2 concentration in each model layer, integrating all layers with the height of each model layer.

Because of noise in the satellite data small retrieved VCD values are highly uncertain. A threshold limit is sought to identify those regions that have a significant amount of SO_2. Standard deviation for the satellite data is calculated over an apparently SO_2 free North Atlantic region (size 10 x 15 degrees lat lon respectively), and is found to be around 0.13 DU. Effects of varying cloud cover are ignored. An instrument detection limit is three times the standard deviation of a blank, so we assume that with a threshold value set to 0.4 DU we exclude satellite data below detection limit. Any grid point with a value over this threshold in the satellite data is used along with the corresponding model data. Daily mass burdens for the North Atlantic region are calculated by summing up all the SO_2 VCD in the grid cells above the threshold. One DU is 2.69 10^{20} molecules per square metre, which corresponds to a column loading of 28.62 milligrams SO_2 per square meter (mg/m^2).

Station data of SO_2 surface concentrations are collected by the European Environment Agency (EEA) through the European Environment Information and Observation Network (EIONET). We make use of two preliminary subsets of this data, one obtained from work within the MACC project to produce regular air quality forecasts and reanalysis, and a second one obtained from EEA as so called up-to-date (UTD) air quality data base, state spring 2015. The two different subsets cover observation data from different countries, and have not yet been finally quality assured at the time of writing this paper. We use only station data, which

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contain hourly data, however there are missing data and some stations have instruments with high detection limits making it difficult to create a continuous measurement series with good statistics. Therefore, in this study some outstanding episodes with high concentrations of SO_2 are analysed. Model data are picked consistently from gridded hourly data at model surface level.

3 Results

3.1 Comparison to satellite data

Observations by satellite provide information about SO_2 location and column density. Figure 1a shows as an example the VCD from the OMI satellite overpasses on 24 September, Fig. 1b and Fig. 1c show the modelled and the adjusted VCD from the control run (hol_ctrl). The observed satellite SO_2 cloud and the model simulated SO_2 cloud show similar shape and location. The adjusted model column densities are smaller than the original model VCDs. More weight is given by the averaging kernel to model layers higher up, close to the reference height of 7km, where there is less SO_2 in our case, with emissions and transport happening in the lower part of the troposphere. The reduced column densities are more comparable to the column densities observed by the satellite, there are however some differences of where the maximum column densities are located.

A quantitative comparison is attempted here by integrating all satellite - and corresponding model data - above the North Atlantic, between Iceland and Europe, into daily mean column loads. Figure 2 shows time series from September to October of daily satellite coverage and daily mass burdens considered over the area where satellite VCD values exceed the 0.4 DU detection limit as explained above. The area covered by satellite observations at the beginning of the period is around 70 percent of the domain used here (red boxes in Fig. 1). Towards the end of the period, the satellite coverage is only around 40 percent because of the increasing solar zenith angle (a satellite zenith angle cutoff of 75° is used for the satellite data). On some days, the satellite cover is even lower because of the OMI zoom mode. The percentage of the satellite data that is above the detection limit is low over the entire two month period, only reaching around ten percent at the end of September and at the beginning of October.

On most days, the satellite daily mass burdens are above the model value, not including the days where the zoom mode minimizes the coverage. The average mass burden adjusted to the 7 km reference height for satellite data are 11.17 kt SO_2 for satellite and 8.72 kt SO_2 for the

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model. The highest values are at the beginning of the period, decreasing over time, for both observed and model mass burdens. Especially during October the values are declining. At the same time the satellite coverage is decreasing. To further investigate whether the increasing solar zenith angle is responsible for the increasing bias of the simulated versus observed VCDs, a new domain further south is used. All that area where satellite observations may be possible until the end of October (61.25^{o} north) is used to calculate another set of daily column loads for satellite and model data (see Fig. 2c). Satellite coverage in this southerly domain is not decreasing over time, but it is also not covering Iceland, so the SO_2 from Holuhraun needs to be transported south to be detected. The plume is transported south four times over the two-month period as the peaks in column load values show. In this southerly area the daily accumulated mass burdens are similar in September and in October, supporting the idea that the decrease in mass burden in Fig. 2b is due to reduced satellite coverage. Taking into the account the area in which the satellite observed SO_2 above detection limit, the satellite average column loads are calculated as around 70 mg/m^2 for the start of the period and on 19 September, model values are lower. Also the peaks in the middle of October in Figure 2b have a satellite average column value at 62 mg/m^2.

Percentile values from the distribution of the daily mass burden in September and October 2014 from all the three model simulations, original and kernel weighted are shown in Fig. 3. The kernel weighted model data can be directly compared to the percentile characterisation of the satellite data. As illustrated in Fig. 1, there is a clear decrease in the column load values before and after the averaging kernel is applied, because the SO_2 plume was found much below 7 km altitude. The differences between the three model simulations however change before and after the satellite kernel is applied. For the original model data, the model simulation with emissions in the lowest kilometre (low_hol) has the highest daily mass burden values, while the run with the emission highest in the atmosphere (high_hol) exhibits a lower mass burden than the two other. The higher values in the low_hol simulation can be explained by less wind and dispersion at low altitudes and thus a more concentrated SO_2 cloud than in the two other model simulations. After the averaging kernel is applied to the model data, the high_hol model simulation has the highest daily values compared to the other two model simulations. High values in satellite data, and model data with kernel profiles applied reflect high concentrations and/or volcanic SO_2 at high altitudes.

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Comparing the satellite data to the kernel weighted model data; the satellite 75th percentile is higher than the model 75th percentile. The median for the ctrl_hol, low_hol and high_hol daily mass burden are 7.38 kt, 4.43 kt and 8.34 kt respectively, for satellite the mass burden median value is 7.03 kt. The satellite data therefore have higher maximum values that results in the higher average values and the 75th percentile, most of the satellite daily mass burden values are however around the model data for the ctrl_run. From all the model simulations, with different emission heights, the ctrl_run is the most similar to the satellite data.

3.2 Surface concentrations

SO_2 from the volcanic eruption on Holuhraun was measured at several surface stations during the period. Three different episodes with clear peaks in observed concentrations at stations around Europe are described in the following paragraphs. Exemplary comparisons are shown and additional comparisons at other stations are available in the supplementary material.

Figure 4 shows hourly time series for two stations over Great Britain and France from 20 September to 26 September. On 21 September 16 UTC, high SO_2 concentrations were measured at the station in Great Britain. The station is situated in Manchester near the west coast of Britain. None of the three model simulations exhibits exactly the same values as observed. Although the model simulations do not reach the observed maximum values, the model field shows areas south of the station nearby Manchester, where the SO_2 concentrations only due to the volcanic eruption are around 50 µg/m^3. Interestingly, the agreement of the model derived volcanic SO_2 time series is better in agreement with measurements than the total simulated SO_2 concentration (grey curve), indicating that the model may not resolve transport from nearby pollution sources and that the station for these days is rather representative of long range transported SO_2. The next day, the plume has moved further south over France. The French station is situated on the west coast of France in Saint-Nazaire. The measurements show three peaks over three days, with the highest one measured 12 UTC 23 September. All the three model simulations have the peak concentrations earlier than the observed, and the concentrations from the model are lower than observed. The three simulations do however show increased concentrations at the site due to the volcanic eruption over the three days. The map shows that large parts of France had an increase in SO_2 surface concentrations during this time.

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Figure 5 shows the time series for three stations over Scotland and Germany a month later, from 20 to 26 October. The high_hol simulation shows low concentrations over the Scottish Grangemouth station, but the ctrl_hol and low_hol have a plume with high concentrations over the station on 20 October. There are no measurements at this time to compare the model values to. The timing of the second plume 21 October for the two models is a few hours early and the modelled concentrations higher than the observed, especially for the low_hol simulation. The map shows a narrow plume from Iceland south to Scotland and the station lies on the edge of this plume. On 22 October, the volcanic SO_2 is measured at stations in Germany. Figure 5d shows the plume reaching from Iceland into the North Sea, transported east and south compared to the situation from the day before. The two stations Kellerwald and Bremerhaven experience the plume differently. While for Bremerhaven the peak is short the peak lasts for one day at Kellerwald. The map show that the plume is narrow for all three stations, and the gradient between where there is no Holuhraun contribution and the maximum concentration is strong. At Kellerwald station, the low_hol simulation has the highest concentrations at the beginning of the plume and the high_hol simulation is highest at the end of the plume. The ctrl_hol simulation has the most comparable concentrations to the observed ones, although all the models runs have values that are too high. For the Bremerhaven station, the observed peak is earlier than the modelled, but all the model runs match the last hours of the plume.

A third plume is illustrated in Fig. 6 over Northern Europe, occurring from the end of October to the beginning of November. Figure 6a shows the measured SO_2 concentrations at a station in Oslo, Norway. There are four peaks measured from 29 October to 31, the highest one on 29 October. The models runs show contribution from Holuhraun SO_2 over the same three days, but do not reach the high measured concentrations, especially the first plume is underestimated. On October 30, the plume is transported south east to Poland. The Polish station in Sopot experiences a short peak that the model simulates to happen a few hours earlier. The ctrl_hol simulation has the most comparable concentrations.

Transport to Europe is caused by northerly and north-westerly winds. For the first plume, where the model shows low concentrations compared to the observations, there had been southerly winds a time before strong northerly winds transported the SO_2 cloud south over Great Britain and France. Compared to the other two episodes, the SO_2 surface concentration due to Holuhraun are higher over a larger area during this episode. The difficulty of the model

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to simulate the SO_2 transport correctly depends on the uncertainty in the emission term, the meteorology fields, the chemical reactions and deposition. Overall the comparison at the stations and with the satellite data indicates, that the ctrl_hol simulation, with the assumption that emissions occurred between 0 to 3 km, performs best.

3.3 Effects of the eruption on European pollution

The results above show that, although the Holuhraun eruption released large amounts of SO_2, the stations in Europe often measured the increase in SO_2 concentrations as short peaks. The model makes it possible to find a more general view of the impact in the European air quality due to the volcanic emissions. Table 2 summarizes the model results for Europe. Only grid cells covering one of the 31 countries are considered when calculating the results shown in the table, the emission (from anthropogenic sources), concentration and deposition over the oceans are not studied. Since a large part of the deposition and concentration increase occurs downwind and close to the emission point, the deposition and concentrations over Iceland is given in brackets.

The Holuhraun emission estimate used in this study releases over 4.5 times the anthropogenic emission from the 31 countries (not including ship emissions). The anthropogenic emissions from Iceland are only 18 kilotons, the SO_2 emissions from Iceland increase by over 300 times.

Over the three months, there is 1.32 times more SO_X wet deposition for the control run with Holuhraun emission than the MACC reference with no Holuhraun emission. The wet deposition over Iceland and the rest of Europe is dependent on the emission height. The simulation with the emission highest in the atmosphere (high_hol) has the highest contribution to the rest of Europe, while less than half of the wet deposition falls on Iceland compared to the other two runs. For dry deposition, the ten percent increase over Europe is about the same for all the three model simulations with Holuhraun emissions. For Iceland however, the SO_X dry deposition is very dependent on emission height.

Figure 7 shows the total deposition over Europe for the standard MACC model simulation with no Holuhraun emission (no_hol), the control model simulation (ctrl_hol), and the percent increase for these two model runs. For the no_hol simulation, the highest depositions are over central and Eastern Europe, while the areas with the lowest deposition are over Iceland, northern Scandinavia and over the Alps. These are also the areas that experience the highest percent increase in addition to the northern part of Scotland. Due to the Holuhraun emissions

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Iceland has the highest SO_X deposition in Europe, and the coast of northern Norway shows depositions on the same level as Eastern Europe.

The averaged SO_2 surface concentration over Europe is under normal condition higher than over Iceland. For the simulations with Holuhraun emission the increase over the rest of Europe is around the same for all three simulations. The ctrl_hol and ctrl_low simulation give high increases over Iceland, while for the high_hol simulation, the average concentration over Iceland is close to the rest of Europe.

The increases in $PM_{2.5}$ concentrations are due to increased sulphate production from volcanic SO_2. Dry production is due to SO_2 reacting to OH, while wet production occurs in cloud droplets. $PM_{2.5}$ concentrations are a collection of all aerosol under 2.5 µm, and sulphur is only a part of the aerosol mass. For $PM_{2.5}$ concentrations, the table shows that Iceland has a lower average than the rest of Europe for all the four runs, even though Iceland is the contributor to the increase in pollution levels. The high_hol model simulation has a higher increase in $PM_{2.5}$ concentration than the two other simulations. Especially the low_hol simulations have high deposition on Iceland, and possibly over the ocean, that will lead to a lower contribution to the $PM_{2.5}$ increase.

The distribution of $PM_{2.5}$ from the no_hol and ctrl_hol simulation, plotted in Figure 8, shows the same polluted and clean areas as in Fig. 7. The percent increase is not as high as for the deposition, but the areas are similar. There is a high increase over north-west Norway and northern Norway, where the increase is over 100 percent. Figure 8b still shows that although the percentage increase is high, the $PM_{2.5}$ concentrations in these areas are among the least polluted in Europe. The high deposition levels in this region indicate that the $PM_{2.5}$ is scavenged out.

WHO recommends a 24 hourly average mean concentration level of 25 µg/m^3 for $PM_{2.5}$ not to be exceeded over three days over a year (WHO,2005). Figure 9a shows that over the Benelux region, Northern Germany and Northern Italy this limit value is exceeded by up to ten days during the three months studied. As the previous plot showed, these are regions with high average $PM_{2.5}$ concentrations. Because the daily concentrations are already high, any increase in days in the model ctrl_hol simulation due to the Holuhraun emissions is also occurring in these regions. The Figure also shows that Northern Ireland experienced up to two exceedance days due to the volcanic eruption.

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4 Discussion

The variances between the satellite model data and the satellite observations can be due to several factors. a) The model emissions flux may be under or overestimated compared to the real emissions, model VCDs are therefore too low / too large compared to the observed ones. b) The areas within which the column mass are constructed depend on the threshold VCD value and the satellite data, so the values in the model depend on the position of the observed SO_2 cloud. If the simulated plume is displaced into an area where the satellite does not show any useful signal, then this part of the model plume is ignored and may lead to underestimates of the model. c) The presence of clouds can increase the uncertainty of the satellite retrieval. d) The unknown real height of the SO_2 plumes may introduce additional bias between model and satellite VCDs.

Our Holuhraun emission term in the three model simulations is constant throughout the simulations both with respect to emission height and emission flux. Maximum fluxes of 1300 kg/s were reported by Barsotti (2014), and Gislason et al. (2015) estimated a 2.5 times the average emission term during the first two and a half weeks of the eruption. The assumption of a constant emission term is thus certainly a simplification. The emission height is also variable, dependent on initial volcanic eruption characteristics and meteorological conditions like wind speed and stratification (Oberhuber et al. 1998). A better source estimate for the eruption is beyond the scope of this study; however the fluctuations in flux magnitude and emission height can explain some of the differences between observed and simulated concentrations, especially at the beginning of September.

Ialango et al. (2015) found that the SO_2 plume from Holuhraun was detectable with a Brewer instrument in Finland and compared the measurements to satellite observations from OMI (Ozone Monitoring Instrument) and OMPS (Ozone Mapping Profiler Suite). From comparing the ground measured SO_2 to the satellite data, the satellite products with an a priori profile placing the SO_2 in the planetary boundary layer gave the best agreement. The reduction in column loads from applying the averaging kernel seen in this study leading to reasonable agreement with the satellite VCDs also shows that the SO_2 was situated well below the 7 km altitude. Further comparison of the modelled SO_2 vertical distribution to measured one, e.g. from IASI, is needed to understand the impact of any bias in modelled vertical distribution on the comparison to satellite derived VCDs. Our sensitivity runs indicate considerable sensitivity of the estimated amount of SO_2 in the North Atlantic area to the vertical

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distribution of the SO_2. This essentially prevents us from using the satellite data to make a more quantitative inverse judgement on the emission strength.

Schmidt et al. (2015) presents a comparison between model, satellite and ground observations for September. Mass burdens from OMI are derived using observed plume heights from the IASI (Infrared Atmospheric Sounding Interferometer) instrument on the MetOp satellite. The model NAME (Numerical Atmospheric-dispersion Modelling Environment), a Lagrangian model, is run for September with sensitivity runs testing both emission height and emission flux. Comparing with the two satellite data sets, the model simulation with doubled emission flux (~1400 kg/s) matches well with the OMI satellite data for the first days, while for the rest of September the model simulation with emission consistent with this paper matches better (~700 kg/s). The satellite comparison presented here shows that although the satellite data have higher daily mass burden values for most of the first days, it is not evident that the emission term on average is too small. The observed plume height presented in Schmidt et al. (2015) by IASI measurements also supports our ctrl_run emission height distribution between the ground and 3 km.

Surface concentration comparisons presented in this study and in the supplementary material show that the volcanic SO_2 was observed as short singular peaks lasting from a few hours to several peaks over a short set of days. The biggest difference for the three studied plumes is for the first one during September over UK and Western Europe, with up to a factor of four differences between simulated and measured concentrations at several of the stations. But both the measured and simulated concentrations during the September event were higher than the two later events, pointing to a different transport of SO_2 in the first event, and not only higher emissions. Schmidt et al. (2015) also presented a model comparison of observed and model concentration for these days, and the results show the same as seen in this study. Even for the NAME model simulation with double emission show smaller concentrations at the stations presented in Schmidt et al. (2015).

The results in this study show that the sulphur depositions from September to November over Northern Norway were at the same levels as the most polluted regions in Europe. Emission ceilings aim set by the Gothenburg Protocol was to reduce the SO_x emissions by 63 % by 2010 compared to the 1990 levels (EMEP, 2015). Most countries have accomplished these reductions, and the sulphur deposition levels over Europe have decreased. The Holuhraun eruption changed the picture in some areas. Comparing observed deposition levels at

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Tustervatn station in central Norway, the simulated deposition is higher than the yearly observed averages since 1980. Monthly observed values at this station during the 2011 Grimsvötn eruption show almost as high values as the ctrl_hol simulation. The increase in SO_x deposition at Birkenes station in Southern Norway is negligible. Northern Norway is more susceptible for volcanic impact because of the geographical position, in addition to high frequency of precipitation on the western coast of Norway. Comparing the mean deposition levels over the three months in 2014 over Norway to model simulations with emissions from previous years, they are double to the early 1990s (EMEP, 2015). Southern Norway experienced a sulphur deposition decrease of 40 % from 1980 to 1995 due to emission abatement in Europe (Berge et al. 1999). The highest contributors to high deposition levels over Southern Norway were the UK and Germany (18 % and 15 % respectively). Norway also experienced in 2014 a high percent increase in $PM_{2.5}$ concentrations. The $PM_{2.5}$ levels over Scandinavia are low, and a small increase in the concentrations leads to high percent increases. The increase over land shows a similar pattern as the results found in Schmidt et al. (2011) for a hypothetical Laki eruption. Even though the highest increase is over Scandinavia and Scotland, the concentrations are too low to exceed the 25 $\mu g/m^2$ limit. Already polluted regions like the Benelux region experience more days with exceedances as well as North Ireland.

5 Conclusions

The increase in SO_2 caused by the volcanic eruption at Holuhraun were observed by satellite and detected at several stations over Europe. Model simulations with the EMEP/MSC-W model with emissions from Holuhraun over the period from September to November have been done to investigate the model capability to simulate such events, and also to study the impact of the increased emissions on concentrations and depositions over Europe.

The first two months of the model simulations are compared to satellite retrievals from OMI. The retrievals use an assumed plume height of 7 km. Averaging kernels from the satellite data are applied on the model data to compare the model data to the satellite. Because of the weighting, the satellite retrieved mass burden values are dependent on both vertical placement and amount of SO_2. Two sensitivity model simulations with different Holuhraun emission height are compared to the satellite data together with the control simulation. The results show the importance of weighting the model data with the averaging kernel when comparing the model to satellite VCD. The combined uncertainty in emission strength and height impact

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when comparing the satellite data to the model simulations makes it difficult to conclude which emission height is most realistic.

The model simulations are compared to observed concentrations at stations over Europe for three different events with high concentrations measured at the stations due to the Holuhraun emissions. For all the events, the timing of the model peaks is well compared to the observed peaks in concentration. For the two model simulations with emissions distributed lowest in the atmosphere, a better timing can be seen than for the sensitivity run with the highest emission height. Due to the transport of SO_2 during the first event, both the model data and measurements are higher than during the two latter events. The biggest difference in concentration between observed and simulated values is also seen during this first plume reaching Europe. Uncertainties in the model simulations increase by the length of transport, and some near misses of the narrow plumes can clearly explain differences between model and observation. Also, to make a better estimate of the model performance during the whole volcanic eruption, better quality checked station data is needed.

The change in pollution levels over Europe due to the increase in emissions due to the volcanic fissure is studied. Of the parameters studied, SO_X wet deposition showed the highest increase. For the control simulation there is 32 % times more sulphate wet deposition than the model simulation with no Holuhraun emission over the 28 European Union countries, Norway and Switzerland. The regions that have the highest increase, apart from Iceland, are Northern Scandinavia and Scotland, regions that are among the least polluted in Europe. Especially the coast of Northern Norway, with a percent increase in total deposition of over 1000%, has levels in 2014 equal to the most polluted regions in Europe. Compared to measurements, the levels are higher than the yearly averaged measured ones at Tustervatn (Central Norway) since 1980. Compared to model simulations with meteorology and emission from previous years, the mean deposition levels over Norway are double that of 1990.

The difference in SO_2 concentrations over Europe between the no_hol and model simulations with Holuhraun emission are around 13 percent over the same 30 countries and increases occurs as short peaks in concentration levels from a few hours to some days. For $PM_{2.5}$ concentration, the increase is six percent. The biggest difference in percent increase are seen over Scandinavia and Scotland, however these regions are among the cleanest in Europe, also with the added sulphur caused by the Holuhraun emissions. A lot of the sulphur is also deposited out over these regions by frequent precipitation. The areas that show increase in

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days with over 25 µg/m^2 $PM_{2.5}$ concentrations are already polluted. Even though with high emission from the volcanic fissure at Holuhraun, the increases in pollution levels are low over Europe.

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Table 1. Overview of model runs and the Holuhraun emission height assumptions and flux.

Model run name	Holuhraun layer into which SO2 was injected in the model simulation	Holuhraun flux
ctrl_hol	0 - 3 km	750 kg/s
low_hol	0 - 1 km	750 kg/s
high_hol	3 - 5 km	750 kg/s
no_hol		0

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Table 2. Emissions, depositions and concentrations for the 28 European Union member states, Norway and Switzerland for the three months (September, October, November). Emissions and depositions are total over the three month period, concentrations are the mean over the period for the 31 countries. Numbers in brackets are the contribution from Iceland, for emission and deposition, the number represents the sum over Iceland. For concentration, the number represents the average over Iceland.

	no_hol	ctrl_hol	low_hol	high_hol	ctrl_hol/no_hol
Emissions SO_2 (kilotons)	1 257	1 257	1 257	1 257	1
	(18)	(5 980)	(5 980)	(5 980)	(5.68)
SO_X Wet deposition	1 043	1 382	1 285	1 465	1.32
(kilotons)	(11)	(1 122)	(1 491)	(472)	(2.37)
SO_X Dry deposition	481	529	524	526	1.10
(kilotons)	(4)	(151)	(409)	(8)	(1.40)
SO_2 Surface conc.	1.39	1.58	1.56	1.56	1.13
(mean µg/m^3)	(0.59)	(38.95)	(105.91)	(1.81)	(66.17)
$PM_{2.5}$ Surface conc.	5.86	6.20	6.09	6.28	1.06
(mean µg/m^3)	(0.82)	(2.50)	(3.13)	(1.12)	(3.06)

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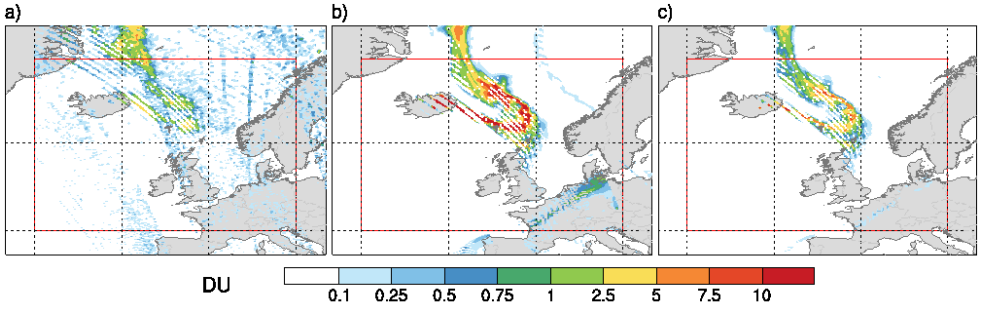

Figure 1. SO_2 column density for a) the satellite swaths on 24 September, b) corresponding model data from 24 September, and c) model data with averaging kernel applied from satellite data. The red box indicates the area where the satellite statistics in fig.2 are done.

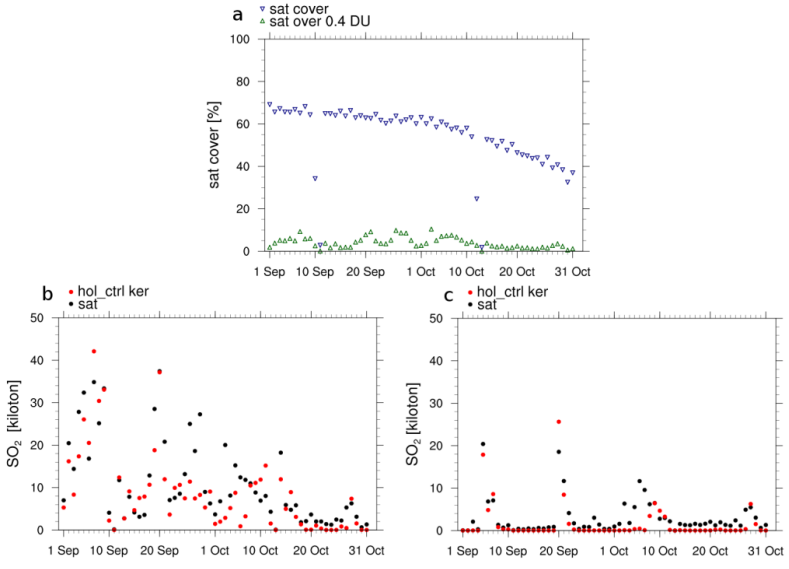

Figure 2. a) Daily time series of satellite observed area coverage (blue triangles) in percent of the total area of the domain used for the statistics (30 W - 15 E and 45 - 70 N, see fig 1).

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Green triangles show the percent of the area where satellite derived SO_2 is above 0.4 DU. b) Daily time series of mass burdens from satellite data (black dots) and from model control run (red dots) with averaging kernel applied, accumulated in consistent area. c) Shows the same as b) but over a smaller area just south of 61.15 degrees north.

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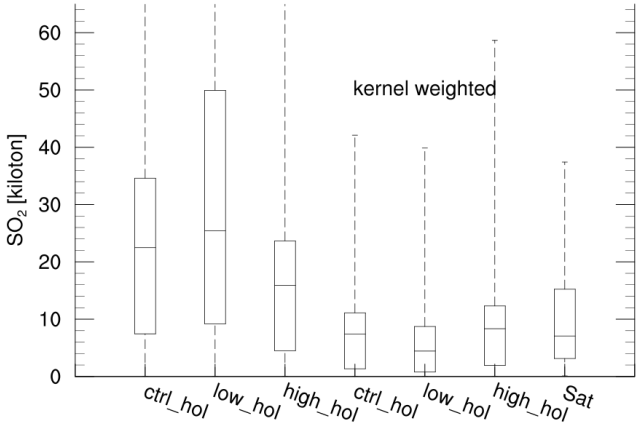

Figure 3. Distribution of mass burden derived from the 61 daily values (see fig 2) for the three model simulations, one for each of the three kernel weighted and the satellite data, in the area where satellite derived SO_2 exceeds 0.4 DU. The boxes shown represent the 25th percentile, the median, and the 75th percentile values, lower whiskers the minimum value and upper whiskers the maximum value.

Percentile statistics derived from the 61 daily mass burden values (see fig 2) for the three model simulations, each of the three kernel weighted and the satellite data, in the area where satellite derived SO_2 exceeds 0.4 DU. Boxes show 25th percentile, median, and 75th percentile values, lower whiskers the minimum value and upper whiskers the maximum value.

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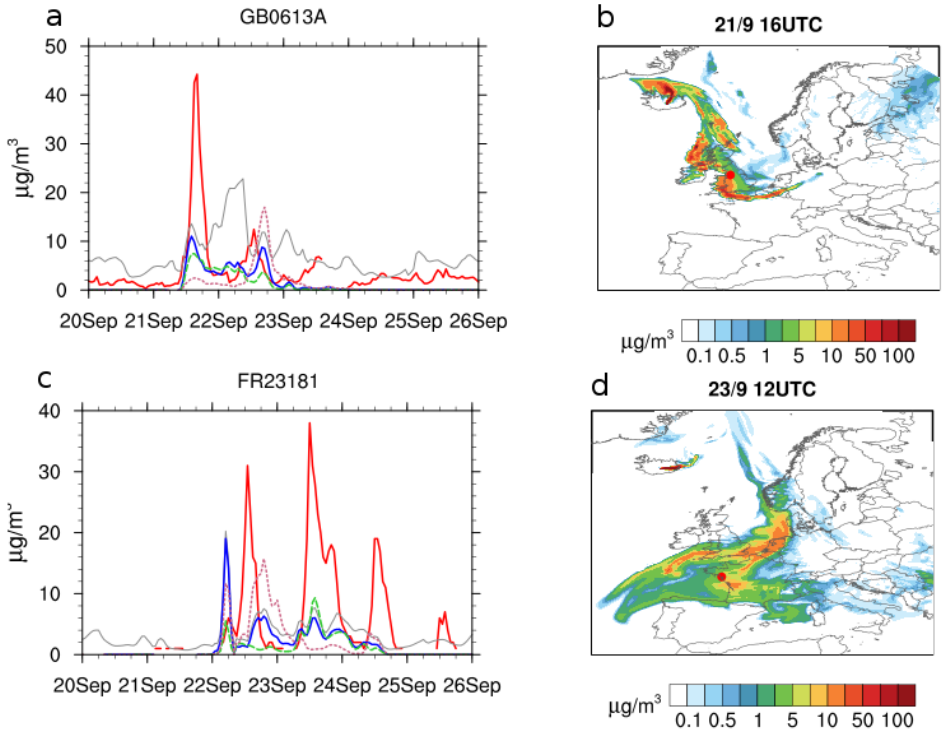

Figure 4. Left: Time Series from 20 to 26 September 2014 for two stations, GB0613A in Manchester and FR23181 in Saint-Nazaire. The red line shows the measured ground concentrations, the grey line represents the modelled ground concentration with ctrl_hol. By subtracting the ground concentrations from the no_hol simulation the concentration due to volcanic eruption for the ctrl_hol, low_hol and high_hol calculated and are shown in the blue, green and pink line respectively. Right: Ground concentration due to the volcanic eruption from ctrl_hol, corresponding to the blue line in the time series, for the time of the maximum observed concentration. The red dot on the map marks the position of the station.

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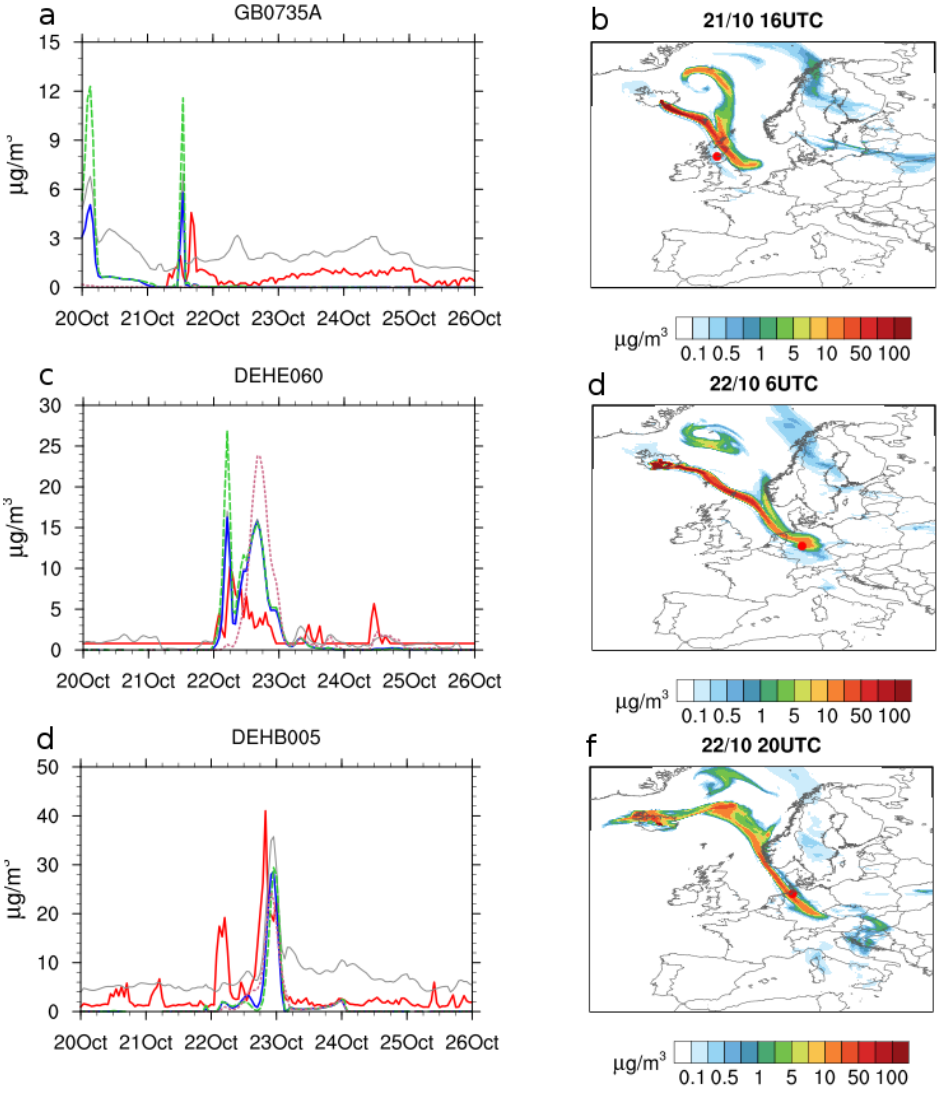

Figure 5. The same as Figure 1, but from 20 to 26 October 2014 for three different stations GB0735A Grangemouth in Scotland, DEHE060 Kellerwald and DEHB005 Bremerhaven in Germany.

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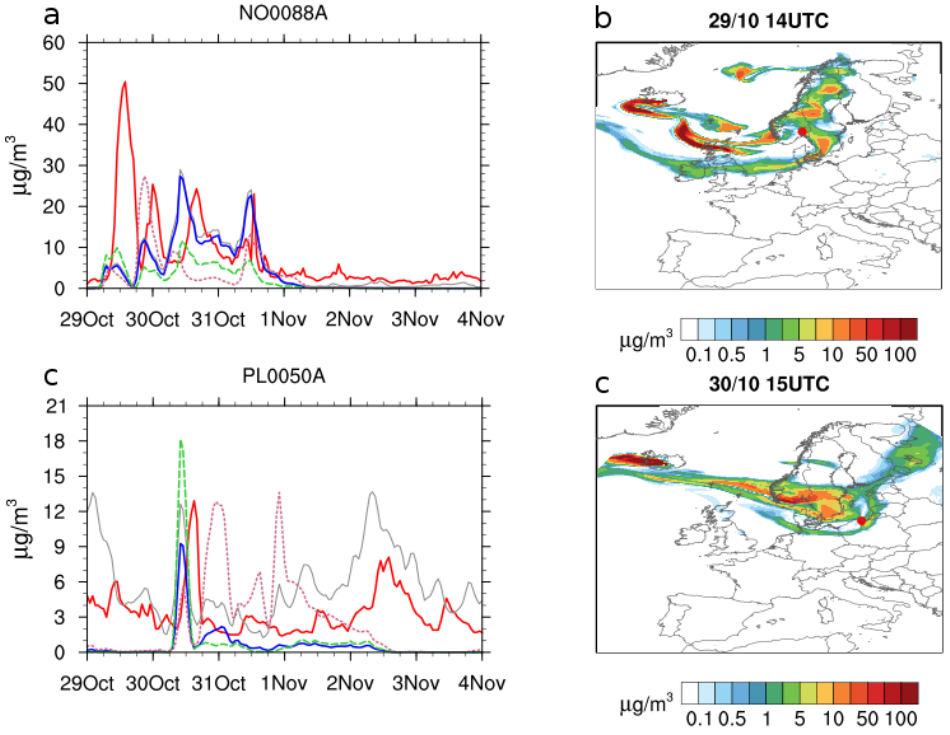

Figure 6: The same as the two previous figures but from 29 October to 4 November 2014 for NO0088A Oslo, Norway and PL0050A in Sopot Poland.

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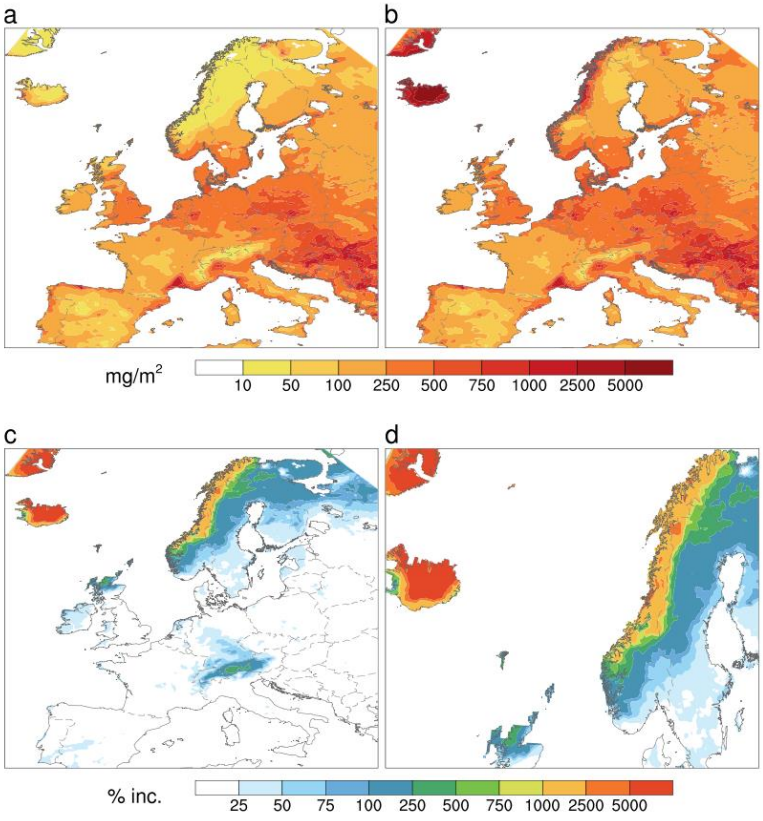

Figure 7. Total deposition of SO_X (wet and dry) over Europe from September to November for no_hol (a) and ctr_hol (b) simulations and the percent increase due to the Holuhraun emissions (c). d) Shows the same as c) but zoomed into Norway and Northern Europe.

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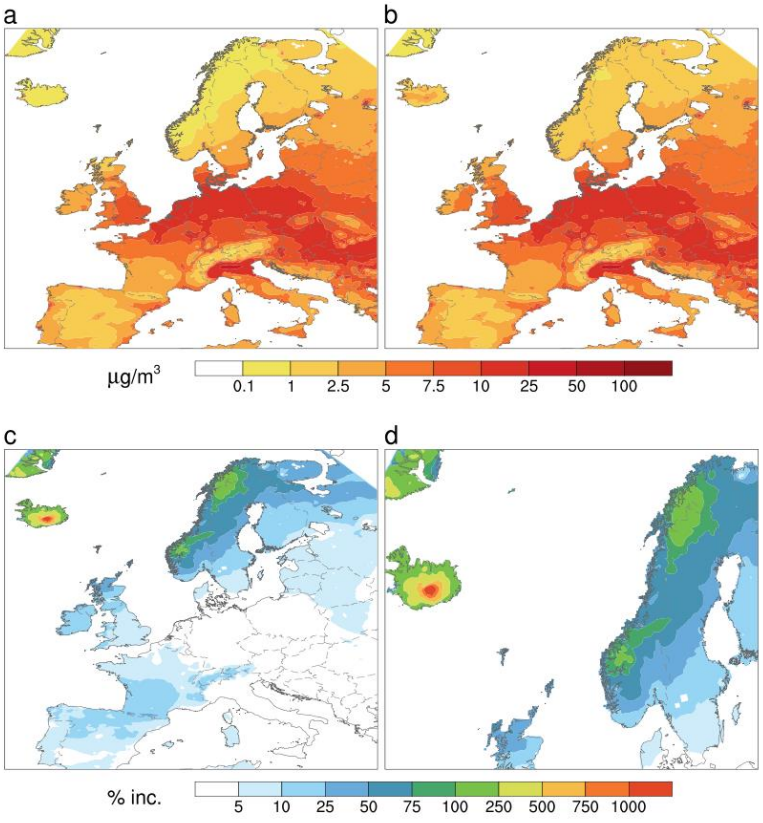

Figure 8. Show the same as Figure 7, but with average $PM_{2.5}$ concentration over the three months.

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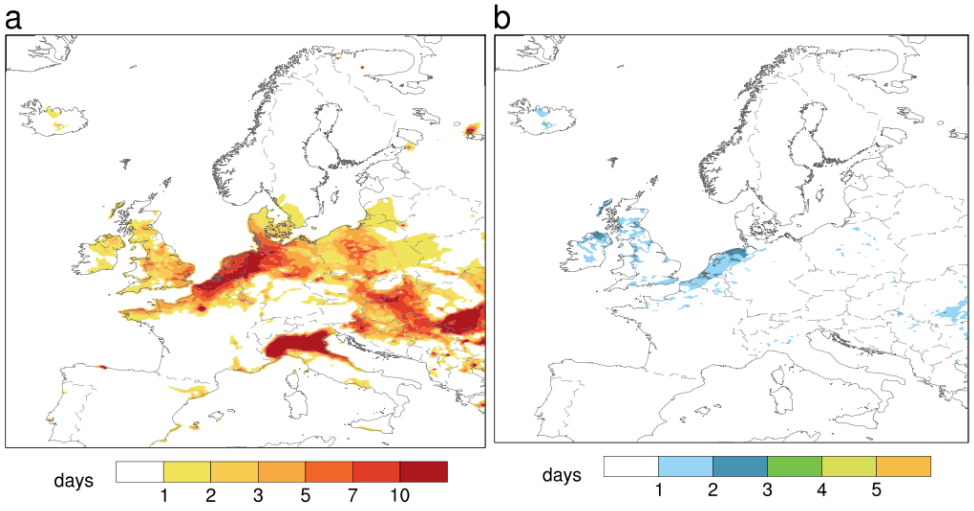

Figure 9. a) Days with exceedances of $PM_{2.5}$ over September trough November for the ctrl_hol model simulation. b) The increase in days from no_hol to ctrl_hol.