Spatial distribution of hydrogen sulfide from two geothermal power plants in complex terrain

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HIGHLIGHTS

- High air stability, low wind speed and low precipitation increased H2S concentration.
- Plumes were narrower with higher concentration over smoother terrain, such as lakes.
- Plumes were observed to be trapped alongside a mountain range.
- H2S plumes were observed to be guided by the terrain during stable conditions.
- Plumes converged due to spatial variability in the wind field.

ABSTRACT

Concerns have arisen about the health impact and odor annoyance of hydrogen sulfide (H2S) emissions associated with geothermal power production. Measurements have been made at stationary measuring stations in inhabited areas but little is known about the spatial behavior of the H2S plumes. This study presents field measurements of the spatial distribution of the ground concentration of H2S within a 30 km radius of two geothermal power plants during 20 distinct events spanning one year. The results showed that high H2S concentration was correlated with high air stability, low wind speed and absence of precipitation. The odor threshold (11 mg m⁻³) was exceeded in all events. The instantaneous measurements exceeded the 24-h average national health limit (50 mg m⁻³) up to 26 km from the power plants. The shape of the measured plumes at the same location was similar between events, indicating repeated patterns in plume distribution. Convergence of plumes was observed due to spatial variability in wind direction. Plumes were found to follow mountain passes and accumulate alongside a mountain range. AERMOD modeling demonstrated that narrower plumes with higher concentration can be expected for smoother terrain, such as lakes, consistent with measurements.

1. Introduction

Development of geothermal energy as a clean and sustainable energy source is growing worldwide. Some concerns have been raised with regard to environmental and health impacts, such as hydrogen sulfide (H2S) emissions to the atmosphere (Kristmannsdottir and Armannsson, 2003; Ermak et al., 1980).

For the past two decades geothermal utilization has been increasing in southwest Iceland in close proximity to the capital of Reykjavik, rural settlements and recreational areas. In 2010 local authorities established a health limit of 50 µg m⁻³ for a 24-h running average (Ministry for the Environment and Natural Resources, 2010) which represents over four times the mean odor threshold of 11 µg m⁻³ (WHO, 2003). Prior research has established the connection between H2S concentration in nearby towns and cities and weather conditions. Olafsdottir and Gardarsson (2013) reported a correlation between H2S concentration and wind speed, air temperature and increasing air stability. Kristmannsdottir et al. (2000) reported a negative correlation with precipitation. Thorsteinsson et al. (2013) found occurrence of high H2S concentration with low atmospheric exchange and autochthonous weather. Field measurements of H2S include stationary measuring stations (Kourtidis et al., 2008; Susaya et al., 2011) and passive samplers (D’Alessandro et al., 2009; Horwell et al., 2005). Latos et al. (2011) used a hand held device for multiple measurements. To the authors’ knowledge, large scale measurements of H2S, up to 30 km distance from the source, have not been reported before.

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Modeling air pollution is an important tool to devise strategies to manage pollution. AERMOD, the recommended model by the US EPA, has been used to model the distribution of various air pollutants including mercury (Heckel and LeMasters, 2011), SO2, NOx and PM10 (Zhang et al., 2008), and VOCs (Venkatram et al., 2009). The model has also been used to determine H2S emission rates, based on measurements (O’Shaughnessy and Altmaier, 2011). AERMOD has been found to perform well for modeling buoyant tall stacks in moderate to complex terrain, where samplers were generally between 2 and 8 km from the source (Perry et al., 2005). Seangkatiyuth et al. (2011) reported that the performance of the model for complex terrain and wind field was problematic for locations more than 5 km from the source. Peralta et al. (2013) found that AERMOD results compared well with measurements when wind direction and speed were stable.

This paper presents results from field measurements of near surface H2S concentration levels within about 30 km distance of two geothermal power plants situated in a mountainous terrain. Spreading, directionality and strength of plumes were analyzed under different weather conditions and in relation to topological ground features. Selected characteristic events were modeled in AERMOD to identify the importance of meteorology and topography. The analysis provides an enhanced understanding of the behavior of H2S plumes in complex terrain and therefore a base for predicting H2S concentration.

2. Methods

2.1. Site description

The study encompasses area up to 30 km from the two geothermal power plants in the Hengill volcanic system. The geothermal power plants Hellisheidi (HH, 260 m.a.s.l.) and Nesjavellir (NV, 180 m.a.s.l.) are 10 km apart, located on each side of Mt. Hengill (max 805 m.a.s.l., Fig. 1). Northeast of the mountain is Iceland’s largest natural lake, Lake Thingvallavatn (84 km²). The NV Power Plant is located near the lake shore in a small valley, with ridges rising 200 m to the west and 100 m to the east. The HH Power Plant is located at the southwest base of Mt. Hengill with Middalsheidi Heath to the west sloping towards the capital of Reykjavik. In the southern part of the area are volcanic fissures with crater rows (Gunnlaugsson et al., 2010). Four local towns are located in the area, in addition to the capital (dark shaded in Fig. 1), as well as a few farms and summer houses. Most of the land is uninhabited, characterized by moss, grass and small shrubs.
Further description of the power plants may be found in Olafsdottir and Gardarsson (2013).

### 2.2. H₂S measurements and analysis

A 12 month measurement program was carried out in 2009 in order to determine the areal extent and strength of geothermal plumes in different wind directions and weather conditions. H₂S measurements were performed along the major highways, at different spatial intervals between events, downstream of the plumes to the northwest, east, south and southwest (black roads in Fig. 1). Measurements were made for 3–4 days in a row (randomly chosen) each month for 1–3 h each day. In total, measurements were conducted on 44 days. A total of 20 events were chosen for further analysis based on the following weather conditions and data availability criteria: (1) steadiness of wind direction during the event; (2) range of air temperature, stability and wind conditions between events; and (3) spatial resolution of the H₂S measurements. Measurements were made with a handheld measuring instrument, Jerome 631-X (Arizona Instruments, USA), which has a 4–7100 μg m⁻³ detection range and a ±4 μg m⁻³ accuracy. Two nearly instantaneous (~20 s) measurements were made at each location and the average concentration was converted using the conversion factor of 1 ppm = 1420 μg m⁻³ H₂S (at 20 °C and 1 atm). The background value of H₂S is zero as the measurement roads are not on a geothermal field.

The calculation of the lateral spread of the plumes was partially limited by the spatial resolution of the measurements and the instruments lower detection limit and accuracy (4 μg m⁻³). The spread was calculated as the distance where the measured profiles exceeded 2 μg m⁻³ or half the accuracy of the measuring instrument. For further clarification of the plume spread in a northwest direction, a stationary H₂S measuring station, located in the capital area 4–5 km southwest of where the measurements started (Xnw1, Fig. 1) was used.

#### 2.3. Weather data and analysis

Wind and air temperature data from weather stations at Middalsheidi Heath (Station M), Hellsheidi Heath (Station H) and Mt. Blafjoll (Station B) (see Fig. 1), measured at 10 min intervals, were obtained. Accumulated hourly precipitation was obtained from the weather station at Héllisskard Pass, 2 km northwest of Station H. Ceiling height and cloud cover was measured every 3 h in Reykjavik, about 30 km from the power plants. Bi-daily upper air data were measured at Keflavik airport, about 60 km southwest of the power plants. All weather data were provided by the Icelandic Meteorological Office except for data from Station H, owned by the Icelandic Road Administration.

Solar radiation is always moderate or slight at the northerly latitude of Iceland, such that very unstable air conditions rarely occur. In winter, the air can be stable during the day. The Pasquill air stability class during the selected events was estimated by calculating two local air temperature gradients, from ground to the 925 hPa height measured at Keflavik Airport for both Station M and H, and categorizing them according to Woodward (1999). In addition, the upper air temperature profile at Keflavik Airport at noon was plotted and compared to the adiabatic lapse rate. The three air stability estimates were generally consistent within one stability class.

#### 2.4. Modeling with AERMOD

The American Meteorological Society-Environmental Protection Agency Regulatory Model (AERMOD) is a steady state Gaussian plume model aimed at short range (under 50 km) dispersion of airborne pollutants (US EPA, 2004). The model, with the commercial interface AERMOD View, version 8.2 (Lakes Environmental Software, Canada), was run for selected events for comparison with measurements.

AERMOD has two pre-processors, AERMET and AERMAP. AERMET calculates boundary layer parameters (e.g. mixing height) based on hourly surface weather data, cloud cover, ceiling height, upper air data, surface albedo, surface roughness and the Bowen ratio. The smallest time resolution in AERMOD is 1 h, which was used for comparison with the instantaneous measurements. The median wind direction, mean wind speed and mean temperature in each event, found from 10 min data, were set as the hourly surface weather data for the hour run by the model to best represent the weather conditions during each event. The plumes from NV and HH Power Plants were modeled with data from Station M and H, respectively. Variable surface roughness was used based on the topography downstream of each power plant. The Wieringa-Davenport roughness classification (Wieringa, 1992) was used for the modeling. Given the volcanic landscape the classifications used were “Roughly open” (20 = 0.1 m) to the northwest and “Rough” (20 = 0.25 m) to the east, except when the plume traveled partially over water, when “Sea” (20 = 0.00002 m) classification was used to calculate the total roughness. The Bowen ratio was set equal to 1 and the albedo to 0.2 based on measured summer values at Gunnars hl (South Iceland) by Aradottir et al. (1997). The terrain data input was on a 25 m grid used by AERMAP to calculate the terrain height for each receptor location and the receptor grid had 0.5 km spacing in all modeled events.

The key H₂S source input data for AERMOD from the cooling towers at HH and NV Power plants are presented in Table 1. The H₂S gas is vigorously mixed with the steam in four closely spaced outlets, with fans to accelerate the emission and cool the water further. The outlets were modeled as one point source (for each power plant) with a combined area of all four outlets. The gas exit temperature used was the steam temperature and the velocity was calculated from the airflow through the fans on top of the cooling towers.

The reported annual H₂S emissions from each power plant (Arnalds and Sigurardottir, 2011) were converted to monthly emissions proportionally to monthly reported power generation. The emissions at the NV Power Plant ranged from 311 to 405 g s⁻¹, with a median of 399 g s⁻¹, and at the HH Power Plant from 218 to 289 g s⁻¹ with a median of 279 g s⁻¹.

The modeled pollutant type in AERMOD was set to “other” as no option was available for hydrogen sulfide. The model treats the gas as inert and does not account for oxidation, washout or density, although the density of H₂S is 18% higher than that of dry air.

#### 3. Results and discussion

#### 3.1. Northwestward distribution

Steady H₂S plumes towards the northwest were measured during eight separate days, summarized in Table 2. The events were

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Hellaheidi</th>
<th>Nesjavellir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base elevation (m.a.s.l.)</td>
<td>258</td>
<td>176</td>
</tr>
<tr>
<td>Release height (m above ground)</td>
<td>13.8</td>
<td>13</td>
</tr>
<tr>
<td>Stack inside diameter (m)</td>
<td>19.8</td>
<td>17.8</td>
</tr>
<tr>
<td>Gas exit velocity (m s⁻¹)</td>
<td>8.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Gas exit temperature (°C)</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>
divided into categories based on location and profile shape. Fig. 2 shows the detailed H2S measurements conducted along the road from point Xnw1 (x = 0) to Xnw2 (x = 41) in Fig. 1 for the events in Table 2.

First consider the three events in Category I measured on the far west side of the road during the darkest winter months. Event Ia occurred in the most easterly wind direction, with most divergence between wind directions in the two weather stations (25°) as well as most wind variability (20–35°, Table 1). H2S concentrations (2–16 \( \mu g \text{ m}^{-3} \)) were measured along the first 8 km of road, and a long tail of lower concentrations for another 9 km (Fig. 2). A stationary/portable air quality station at \( x \approx -4 \text{ km} \) (not shown in Fig. 2) reported a concentration up to 8 \( \mu g \text{ m}^{-3} \) during this 1 h measurement period, indicating that the main plume, at a minimum, was 14 km wide. H2S was measured with a steep rise and a minor shoulder along the measurement road in the other two events. The lateral extent of both plumes was around 10–12 km, but the maximum concentrations were double during Event Ic compared to Ib. Both events had almost identical wind directions and wind speeds at stations H and M. The vastly higher concentration in Event Ib than Ic may be contributed to the following factors: 1) less precipitation; 2) higher air stability; and 3) smaller range in wind direction. It is interesting to note that despite almost identical wind directions measured at both weather stations M and H, Event Ic peaked almost 10 km more to the east than Event Ib.

The three H2S distributions in Category II, measured further east along the road, exhibited considerable self-similarity, with concentrations below 5 \( \mu g \text{ m}^{-3} \) for a few kilometers, followed by a steep rise to a maximum and then a slow decrease, either with a shoulder or a short second rise. Interestingly, the more westward location of the maximum concentration did not match the shorter distance to the measurement road or stronger emission from the NV Power Plant, compared to the HH Power plant. The converging distance to the measurement road or stronger emission from the location of the maximum value is where the plumes converge.

The maximum concentration (41 \( \mu g \text{ m}^{-3} \)) was measured in Event Ila during moderately unstable air conditions and a light varying breeze (1–3 m s\(^{-1}\)), 60–70° wind range). The maximum concentrations were similar in Events IIb-c, about 25 \( \mu g \text{ m}^{-3} \). As expected, the lateral spreading of the plumes during unstable conditions (33 km, Ila) was considerably wider than during neutral conditions (22 km, IIb and Iic).

The two Category III plumes, measured farther east, were distinguished by their narrow spread and decisive maxima. Both events occurred during similar weather conditions, except for precipitation. The maximum H2S concentration measured in Event IIIa was 58 \( \mu g \text{ m}^{-3} \) during little precipitation, but only 16 \( \mu g \text{ m}^{-3} \) in Event IIIb during more precipitation in the hour before measurements started. This may indicate that the difference in maximum concentration between the events was due to washout.

### Table 2

<table>
<thead>
<tr>
<th>Category/Event number</th>
<th>Date/Time</th>
<th>Weather Station</th>
<th>Climatic conditions</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Median wind direction (°)</td>
<td>Wind range (°)</td>
</tr>
<tr>
<td>Ia 11-Nov</td>
<td>11:10–12:20</td>
<td>M 113</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Ib 10-Dec</td>
<td>09:30–13:00</td>
<td>H 88</td>
<td>35</td>
<td>3</td>
</tr>
<tr>
<td>Ic 19-Jan</td>
<td>10:10–10:50</td>
<td>M 123</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>Ila 27-Apr</td>
<td>18:40–12:20</td>
<td>H 121</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>IIb 17-Jul</td>
<td>11:00–12:10</td>
<td>H 145</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Iic 18-Sep</td>
<td>10:10–11:20</td>
<td>H 162</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>IIIa 16-Sep</td>
<td>11:00–11:50</td>
<td>H 149</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>IIIb 17-Sep</td>
<td>11:00–12:00</td>
<td>H 161</td>
<td>19</td>
<td>4</td>
</tr>
</tbody>
</table>

**Notes:**

- Total precipitation at Hellisskard Weather Station an hour before measurements started and during the measurements.
- Number of measurements exceeding zero.
- Distance from the NV and HH Power Plants to the location where maximum H2S was measured.
- Distance where the profile exceeded 2 \( \mu g \text{ m}^{-3} \). Estimated from Fig. 2.

**Fig. 2.** Measured H2S concentration along the road northwest of the power plants (x = 0 and x = 41 are marked as Xnw1 and Xnw2 in Fig. 1, respectively).
To summarize, the eight northwest profiles in Fig. 2 and Table 2 suggest a continuous H2S plume of 10—33 km width on the road northwest of the two power plants, as opposed to two distinctive plumes. The H2S distributions exhibited self-similarity along the same sections of the road, generally with a singular decisive maximum and a long shoulder (or minor secondary maximum) which is likely due to the convergence of the two plumes from the power plants. The odor threshold (11 μg m⁻³) was exceeded in all events for up to 13 km on the road in Category II events and the maximum instantaneous concentrations exceeded the 24-h average national health limit of 50 μg m⁻³ up to 18 km away from the plants during two out of eight events. High H2S concentrations were correlated with low wind speeds, high air stability and lack of precipitation both during and in the hour preceding the measurements. The maximum spread was measured during unstable conditions 16—18 km downstream of the plumes (IIa), consistent with the theory that lateral dispersion increases with distance from source and air instability.

3.2. Eastward distribution

H2S plumes propagated east during four events. Table 3 summarizes the climatic conditions and H2S measurement statistics

![Fig. 3. Measured H2S concentration along the road east of the power plants (x = 0 and x = 41 are marked as Xe1 and Xe2 in Fig. 1, respectively).](image-url)

Table 3

<table>
<thead>
<tr>
<th>Category/Event number</th>
<th>Date</th>
<th>Weather Station</th>
<th>Median wind direction (°)</th>
<th>Wind range (°)</th>
<th>Mean wind speed (m s⁻¹)</th>
<th>Mean temperature (°C)</th>
<th>Precip. (mm)</th>
<th>Stability class</th>
<th>Max H2S (μg m⁻³)</th>
<th>Nₐₑ⁻¹</th>
<th>Distance from NV (km)</th>
<th>Distance from HH (km)</th>
<th>Plume width (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVa</td>
<td>19-Feb</td>
<td>M</td>
<td>241</td>
<td>10</td>
<td>7</td>
<td>-1</td>
<td>D/E</td>
<td>4</td>
<td>13</td>
<td>34</td>
<td>15</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>IVb</td>
<td>10-Nov</td>
<td>H</td>
<td>247</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>E</td>
<td>2</td>
<td>11</td>
<td>48</td>
<td>12</td>
<td>22</td>
<td>7</td>
</tr>
<tr>
<td>Va</td>
<td>12-Aug</td>
<td>M</td>
<td>281</td>
<td>15</td>
<td>6</td>
<td>11</td>
<td>C/D</td>
<td>11</td>
<td>10</td>
<td>29</td>
<td>15</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Vb</td>
<td>13-Aug</td>
<td>M</td>
<td>287</td>
<td>24</td>
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<td>13</td>
<td>C/D</td>
<td>11</td>
<td>16</td>
<td>16</td>
<td>17</td>
<td>22</td>
<td>21</td>
</tr>
</tbody>
</table>

a Total precipitation at Hellisskard Weather Station an hour before measurements started and during the measurements.

b Number of measurements exceeding zero.
c Distance from the NV and HH Power Plants to the location where maximum H2S was measured.
d Distance where the profile exceeded 2 μg m⁻³. Estimated from Fig. 3.

Table 4

<table>
<thead>
<tr>
<th>Category/Event number</th>
<th>Date</th>
<th>Weather Station</th>
<th>Median wind direction (°)</th>
<th>Wind range (°)</th>
<th>Mean wind speed (m s⁻¹)</th>
<th>Mean temperature (°C)</th>
<th>Precip. (mm)</th>
<th>Stability class</th>
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<tr>
<td>VIa</td>
<td>07-Dec</td>
<td>M</td>
<td>299</td>
<td>168</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>F</td>
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<tr>
<td></td>
<td>09:50—10:50</td>
<td>B</td>
<td>47</td>
<td>28</td>
<td>3</td>
<td>-1</td>
<td>0</td>
<td></td>
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<tr>
<td>VIb</td>
<td>18-Jun</td>
<td>M</td>
<td>357</td>
<td>9</td>
<td>8</td>
<td>10</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:30—13:30</td>
<td>H</td>
<td>335</td>
<td>13</td>
<td>7</td>
<td>10</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>VIIa</td>
<td>20-Oct</td>
<td>M</td>
<td>328</td>
<td>17</td>
<td>6</td>
<td>2</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13:00—15:20</td>
<td>B</td>
<td>31</td>
<td>23</td>
<td>5</td>
<td>2</td>
<td>0</td>
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</tr>
<tr>
<td>VIIb</td>
<td>08-Dec</td>
<td>M</td>
<td>76</td>
<td>10</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>11:20—12:40</td>
<td>H</td>
<td>51</td>
<td>4</td>
<td>9</td>
<td>2</td>
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<tr>
<td>VIIc</td>
<td>23-Oct</td>
<td>M</td>
<td>49</td>
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<tr>
<td></td>
<td>12:00—14:00</td>
<td>H</td>
<td>24</td>
<td>10</td>
<td>8</td>
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<td>VIII</td>
<td>21-Oct</td>
<td>M</td>
<td>248</td>
<td>160</td>
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<td>H</td>
<td>18</td>
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<td>5</td>
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<tr>
<td></td>
<td>14:40—16:40</td>
<td>B</td>
<td>34</td>
<td>38</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Total precipitation at Hellisskard Weather Station an hour before measurements started and during the measurements.
and Fig. 3 shows detailed H$_2$S measurements conducted on the road east of the power plants from the northerly point Xe1 ($x = 0$) to the southerly point Xe2 ($x = 41$) in Fig. 1.

The NV Power Plant plumes for the two Category IV events, measured to the north along the road, crossed Lake Thingvallavatn, while the HH plumes generally crossed an uneven mountainous terrain. Both events show sharp and distinct maxima associated with the emission from the NV Power Plant, which was located 10 km closer to this section of the road than the HH Power Plant. Plume IVa also demonstrates a secondary peak, corresponding to less than 1/3 of the first spike (34 $\mu$g/m$^3$) with a total spread of about 13 km. Profile IVb, however, does not exhibit a distinct shoulder or secondary peak and has a considerably narrower lateral spread (7 km) and a higher maximum concentration 48 $\mu$g/m$^3$. As discussed in Category I events, the higher measured maximum concentration in Event IVb than IVa was likely associated with less precipitation, lower wind speeds and higher air stability (Table 3). It is interesting to note, however, that the drop in maximum concentration as a result of precipitation was not as strong as in Category III, despite similar rainfall differences (0.9 mm). This could be because the most of the precipitation (0.9 mm) in Event IVa fell during the latter part of the measuring time (from 9 to 10 am), as opposed to falling in the hour preceding the event. The converging winds between Station H and Station M in Event IVa may explain the close proximity of the secondary peak associated with the HH Power Plant emissions. However, diverging winds, greater range in wind direction and less stable air may all have contributed to the fact that the HH plume was not detected in Event IVb.

The Category V events were measured farther south on the same road. Event Vb had a wide profile with H$_2$S concentrations between 10 and 16 $\mu$g/m$^3$, extending about 12 km, with no decisive maximum and a total spread of 21 km. Event Va has a somewhat narrower plume spread (12 km) and a more decisive maximum of 29 $\mu$g/m$^3$. The wind range was larger in Event Vb than Va, which may have contributed to more spreading and lower concentrations.

To summarize, the locations of eastward plumes were strongly determined by median wind direction. Category V plumes spread over a wider region with elevated concentrations but had lower maxima than Category IV, both may be attributed to less stable air. A secondary plume was observed in Event IVa, which can be explained by convergence of the winds instead of diverging as in Event IVb, where the plume from HH Power Plant was not detected.

### 3.3. Southerly- and Southwestward distribution

Six measured events with H$_2$S plumes directed towards the south and southwest are summarized in Table 4. The events were categorized based on whether a major part of the plume was measured along Road 39 south of the HH Power Plant (Category VI), along Road 417 southwest of HH Power Plant (VII), or along both roads (VIII) (see Figs. 1 and 4). The climatic conditions measured at three different weather stations are summarized in Table 4, including mountain Station B which is southwest of the HH Power Plant, at elevation 530 m.a.s.l. The terrain to the south and southwest is more complex than for the other directions as mountain ranges lie alongside the plume direction with identifiable plume pathways. The difference in wind direction between Stations H and
B ranged from 7 to 99, demonstrating the spatial variability in the wind field south of the power plants.

Fig. 5 shows the detailed H2S measurements conducted along Road 39 from point Xs1 (x = 0) to Xs2 (x = 23) in Fig. 1 for events in Categories VI, VII and VIII. In Event VIa, H2S was only detected along Road 39 after about 8 km, where the road starts to bend towards the east, indicating that the initial plume path was along Path I in Fig. 4. The concentration decreased for about 2 km but then increased again to a maximum of 127 μg m⁻³ at the bottom of a slope (Fig. 5, lower panel). High concentrations (above 50 μg m⁻³) were measured for about 6 km. The air stability was moderately stable with an inversion up to about 80 m.a.s.l. at Keflavik Airport. Wind speeds were low at all stations. These weather conditions restrict vertical movements such that the plume is guided by the terrain. The profiles for Events VIIa and VIII along Road 39 rose slowly at first and then steeply at about 10 km to a maximum of 36 μg m⁻³ and 31 μg m⁻³, respectively, and then leveled off. The location of the H2S concentration rise is consistent with Path I (Fig. 4) being the initial plume path, as in Event VIa. The air was less stable in these two events and their concentration decreased further south on the road as opposed to increasing at the bottom of the slope as in Event VIa. All events in Category VII show decreasing concentrations within the first 5 km of Road 39 in Fig. 5. All events recorded a more easterly wind at Station B than at Station H (Table 4), indicating that an initially southwest flowing plume could turn off towards the west, south of the HH Power Plant and thereafter be measured on Road 417. This possible plume path is depicted in Fig. 4 (Path II).

Fig. 6 shows the detailed H2S measurements conducted along Road 417 from point Xsw1 (x = 0) to Xsw2 (x = 26) in Fig. 1 for the events in Categories VII and VIII. In Event VIIa, overall continuously decreasing concentrations along Road 417 may indicate that the plume was aligned along the direction of the road consistent with standard plume theory. The measured fluctuation along the way may be explained by the road winding, resulting in measurements being conducted at different distances from the plume center.
concentrations were elevated (>40 µg m⁻³) in the first 15 km and reached 75 µg m⁻³ at x = 23 km (26 km from source). In Event VIIb the concentration had a steep rise to a maximum of 64 µg m⁻³ with a total spread of roughly 7 km. This narrow spreading of the plume indicates that the plume path was more perpendicular to the road than along it as in Event VIIa. Profiles VIIc and VIII gradually rose to about 20 µg m⁻³ at x ≈ 6 km and maintained this concentration for about 10–20 km, contradicting the theory that concentration decreases with distance from source. This may suggest possible trapping of negatively buoyant H₂S alongside Mt. Blafjoll. Event VIII was the only event detected along both Roads 39 and 417. The wind direction at Station B was more from the north than in Category VII but the wind range at Station H was considerably larger (113°) indicating that the plume may have been split during the measurement time rather than changing direction on the way as discussed for the Category VII events.

To summarize, the plume was observed to be guided by the terrain through mountain passes and along ridges south of the power plants. An instantaneous maximum concentration of 127 µg m⁻³ was measured during thermal inversion. This value was 2–3 times greater than the 24-h average national health limit of 50 µg m⁻³. However, these measurements are not a confirmation of the national health limit being exceeded as they were instantaneous measurements and not daily averages. In two events (VIIc and VIII) the concentration was steady and elevated (~20 µg m⁻³) for 10–20 km which might indicate trapping of the plume alongside a mountain range. One event (VIII) indicated splitting of the plume on either side of Mt. Blafjoll. Plumes were shown to deviate from Road 39 to the west onto Road 417 when easterly winds were recorded on Mt. Blafjoll (Station B). Hence, these measurements highlight a complex spatial wind field in complex terrain, which may lead to the fate of H₂S being heavily dependent on the terrain, especially during slightly stable or moderately stable conditions when the vertical distribution of the plume is constrained.

### 3.4. AERMOD modeling

The plume measurements suggested that differential roughness (land vs. water), spatial variability in the wind, and terrain obstructions are factors that may affect H₂S concentrations in the vicinity of geothermal power plants. Three characteristic events were modeled using AERMOD with steady weather inputs (Tables 2 and 3) to better understand the effects these factors have on the H₂S distribution. It should, however, be noted that AERMOD is neither able to capture spatial wind variability nor the interplay between the wind and the mountainous terrain so the results are more indicative rather than absolute.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Maximum instantaneous measured H₂S (µg m⁻³)</th>
<th>Maximum 1-h modeled H₂S (µg m⁻³)</th>
<th>Distance ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVb</td>
<td>10-Nov</td>
<td>48</td>
<td>28</td>
<td>1.5 km</td>
</tr>
<tr>
<td>IIb</td>
<td>17-Jul</td>
<td>24</td>
<td>7</td>
<td>1 km</td>
</tr>
<tr>
<td>IIIa</td>
<td>16-Sep</td>
<td>58</td>
<td>7</td>
<td>5 km</td>
</tr>
</tbody>
</table>

² Distance between measured and modeled maximum H₂S concentration.

![Fig. 8. AERMOD modeling of Event IIb.](image-url)
Fig. 7 shows the model calculations for Event IVb. The plumes traveled over different land surfaces as the plume from the NV Power Plant was partly over land and partly over water and was thus modeled as 40% “Sea” and 60% “Roughly open” (Wieringa, 1992) yielding \( z_0 = 0.06 \) m. The HH plume traveled over a rough area modeled as “Rough”. This led to the plume from the NV Power Plant being narrower with a higher concentration in the middle ~10 km away from the source, whereas the plume from the HH Power Plant had the highest concentration near the source and diluted further away (Fig. 7). This indicates that the narrow plumes with relatively high maximums measured in Category IV were the result of low roughness over Lake Thingvallavatn. The lateral spread of the measured plume (7 km for \( >2 \mu g \) m\(^{-3}\)) was fairly well represented by the modeled plume (5 km) from the NV Power Plant however, the modeled maximum was considerably lower than the measured maximum (see Table 5). The weaker plume from the HH Power Plant was modeled to have a 4 \( \mu g \) m\(^{-3}\) maximum concentration on the measurement road but the plume was not detected in the measurements as discussed in Section 3.2.

Fig. 8 shows the model calculations for Event IIb. The wind measured at Stations M and H converged, resulting in one composite plume being modeled, demonstrating that the spatial variability in the wind field may play an important role in the H\(_2\)S plume distribution. The model simulations indicated that the measured west shoulder (\( x = 10–15 \) km, Fig. 2) corresponded to the HH plume, the maxima to overlapping of the two plumes, and the east shoulder to the NV plume. The maximum was less than one third of the measured maximum (see Table 5), which led to an underestimation of plume spreading, based on the distance where the concentration exceeded 2 \( \mu g \) m\(^{-3}\). Lastly, AERMOD did not predict the actual location of the measured maximum, which supports that additional changes in local wind direction may occur between Stations M and H and the northwestern measurement road.

Fig. 9 shows the model calculations for Event IIIa. Similar wind directions were measured at Stations M and H so two distinct plumes were modeled on the road, although the HH Power Plant plume was narrow and was likely missed on the road due to low spatial measurement resolution and perhaps low concentration. The modeled maximum H\(_2\)S value, associated with the NV Power Plant, was eight times lower than the measured value. Perhaps more interestingly, the location of the modeled maximum was 5 km west of the measured one (Table 5). This may indicate that the wind direction within the valley where the NV Power Plant is located followed the valley towards the lake and as the plume exited the valley it turned with the southeasterly winds towards the maximum location (see possible plume path in Fig. 9).

AERMOD was unable to model the events south of the power plants (Categories VI–VIII, Figs. 5 and 6) as the model does not simulate spatial variability in wind direction. The model was not able to capture the plumes being guided along valleys and passes during neutral and stable conditions in the mountainous terrain.

Sensitivity analysis was conducted on surface input parameters as well as emission amounts but none could explain the difference between modeled and measured maximum concentrations shown in Table 5. For example the emissions in Event IVb would need to be about 70% higher during the event than the monthly average used in the modeling, which is improbable given the relative steady operation of the power plants. This discrepancy is probably in large part due to the fact that the measurements are instantaneous and
therefore the maxima should be higher than the one hour averages calculated by the model. Two additional modeling factors were identified that might have contributed to the model underestimation: 1) aerodynamic downwash, which may be formed as hills near outlets of emission can have a strong enough downward component to carry the plume downward, thus increasing ground level concentration (De Nevers, 2000); 2) the density of H$_2$S is 18% higher than that of dry air, which may have contributed to a downward drift towards the surface. Other modeling factors that might, however, partially counteract the first two are: 3) initial plume rise, which may have been larger than the model predicted as it did not account for the condensation of the steam in the atmosphere (Wigley, 1976); 4) washout of H$_2$S which may have had an effect at the cooling tower release point where H$_2$S may have dissolved as steam condensates in the atmosphere. A fifth modeling inaccuracy was 5) data input uncertainties such as a lack of time resolution, especially concerning the H$_2$S emissions. These five factors need to be investigated further and taken into account in modeling H$_2$S emissions from the NV and HH Power Plants to provide more reliable data on, for example where the national health limit will be exceeded in the vicinity of the power plants.

4. Conclusions

Measurements of H$_2$S plumes within a 10–30 km distance from power plants showed that low wind speeds, high air stability and absence of precipitation resulted in higher concentrations. Plumes with wider spread were observed to have lower maxima and were measured during unstable conditions, consistent with the theory that lateral dispersion increases with air instability. An instantaneous maximum concentration of 127 µg m$^{-3}$ was measured during a thermal inversion, which was 2–3 times greater than the 24-h average national health limit of 50 µg m$^{-3}$. The health limit value was exceeded up to 26 km from the source. H$_2$S distributions exhibited self-similarity between events, indicating repeated plume patterns. Some convergence of the two plumes from the power plants was reflected due to spatial variability in wind direction yielding higher concentration. Plumes were observed to be guided in mountainous terrain by mountain ridges and passes. Wind direction was observed to shift considerably over mountain ridges changing the path of the plumes. In two events, during neutral and stable air, the concentration was steady and elevated (~20 µg m$^{-3}$) for 10–20 km alongside a mountain range which may indicate trapping of the plume. Measurements thus indicated that the fate of H$_2$S was heavily dependent on the terrain in mountainous areas, especially during stable conditions when the plume’s vertical distribution was constrained.

AERMOD modeling demonstrated that narrower plumes with higher concentrations further from the source can be expected for smoother terrain, such as lakes, and that plumes may converge leading to higher concentration. The modeling showed the importance of capturing spatial variability in the wind field as well as local terrain.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2013.10.013.

References
