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Concentration of Hydrogen Sulfide from Geothermal Power Plants in the vicinity of Reykjavik City, Iceland, 2007-2009

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ABSTRACT

Gases emitted from geothermal power plants are among the key environmental factors of concern for the development of geothermal power plants. Sulfur gases are of most concern but also trace gas and carbon dioxide (CO_2) emissions. Sulfur is emitted from geothermal areas as hydrogen sulfide (H_2S), and when the areas are developed the emission is increased. H_2S is a volatile compound that may be oxidized in the atmosphere. Several environmental factors influence the H_2S oxidation rate, such as radiation, precipitation, temperature and concentration of other chemicals. Geothermal power production in the vicinity of Reykjavik City has increased considerably during the last few years. Electricity production at Nesjavellir Geothermal Power Plant started in 1998 and in October 2006 the Hellisheidi Geothermal Power Plant started operation and was enlarged in the fall of 2008. The Department of Environment of Reykjavik City started measuring hydrogen sulfide (H_2S) concentration at Grensasvegur Street in February 2006. In August 2007 H_2S measurements started in Hvaleyrarholt, Hafnarfjördur, and in June 2008 in Kopavogur town. The main objective of this paper is to shed light on which parameters influence the concentration of hydrogen sulfide in Reykjavik City and its surroundings.

1. INTRODUCTION

Gaseous sulfuric compounds in geothermal areas exist in the form of hydrogen sulfide (H_2S). When the geothermal areas are developed the hydrogen sulfide is, usually, emitted at a higher rate to the environment than before development (Armannsson, 2002). The hydrogen sulfide has a characteristic smell that can be detected at low concentrations. At about 300.000 $\mu g/m^3$ the sense of smell is lost, at 450.000 – 750.000 $\mu g/m^3$ pulmonary oedema can form with the risk of death (WHO, 2000). No health limit value is set for the concentration of hydrogen sulfide in air in Iceland. The World Health Organization (WHO) has given a guideline value of 150 $\mu g/m^3$ as an average value for 24 hours. WHO also gives a value for the smell to become a nuisance, at 7 $\mu g/m^3$ over a 30 minute average. The hydrogen sulfide is unstable in air compared to sulfur dioxide (SO_2) and if conditions are favorable oxidation may take place (Armannsson, 2002; Kristmannsdottir et al., 2000). The Nesjavellir power plant which is about 20 km east of Reykjavik started hot water production in 1990 and electricity production in 1998. Currently the hot water production is 300 MW and the electricity production 120 MW. The Hellisheidi power plant which is about 15 km southeast of Reykjavik was commissioned in October 2006. Currently the electricity production is 213 MW and hot water production is planned to start in 2010. The power plants and the weather stations used in the study are shown in Figure 1.

In 1993 short term measurements were made of hydrogen sulfide and sulfur dioxide concentrations (Kristmannsdottir et al., 2000) in 10 high-temperature geothermal fields in Iceland, both energy producing and non-producing fields. As a continuation of those measurements, long term measurements (4-6 months) were made in the producing fields of Svartsengi, Nesjavellir, Krafla and Namafjall in 1994-1996. The results show that the hydrogen sulfide concentration depends on both precipitation and wind conditions. Modeling using the data suggested that only a small fraction of the hydrogen sulfide is converted to sulfur dioxide within a 15-25 km radius. However due to uncertainties, for example insufficient number of measurements, the modeling did not give conclusive results.

D'Alessandro et al. (2008) report a rapid decrease of concentration values away from the emission points when analyzing the air concentrations and dispersion pattern of naturally emitted H_2S in the geothermal area of Sousaki (Corinthia, Greece). The decrease was more pronounced in summer than in winter which indicates that it is not only due to a dilution effect, but also to redox reactions favoured by higher temperatures and intense sunlight typical of the summer period.

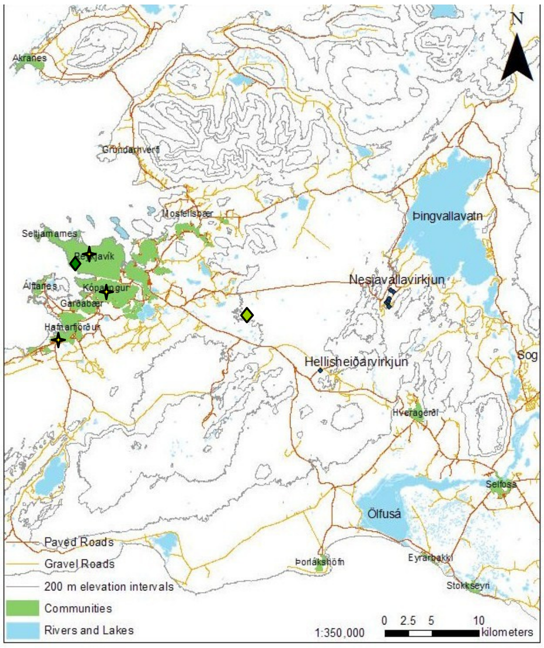

Figure 1. Map of the area showing Grensasvegur measuring station (✧), Kopavogur measuring station (✧), Hvaleyrarholt measuring station (✧) Reykjavik weather station (◆), Middalsheidi weather station (◇), Hellisheidi Power Plant (■) and Nesjavellir Power Plant (■■).

When mapping the distribution of hydrogen sulfide across the City of Rotorua in New Zealand a passive sampler was developed (Horwell et al., 2005). Two of these were located in each square of a grid map of the city. The hydrogen sulfide concentrations could thus be measured simultaneously at approximately 70 locations. The results showed that City of Rotorua can be divided into three zones: A low concentration area in the west, a medium concentration area in the east and a high concentration zone in the centre.

In the 1-million-population city of Thessaloniki, Greece, the H_2S concentrations were measured in the center of the city at a crossing of two major roads (Kourtidis et al.). The highest concentrations of H_2S were observed in winter, while the highest hourly concentrations where observed during the 7:00–9:00 rush hour. Daily mean concentrations in winter were up to 30 µg/m^3, while hourly concentrations were up to 54 µg/m^3.

2. ANALYSIS OF H_2S IN REYKJAVIK CITY

Hydrogen sulfide has been measured in Reykjavik City since February 2006 at the Grensasvegur measuring station; in Kopavogur Town since August 2008; and in Hvaleyrarholt, Hafnarfjördur, since August 2007 (see Figure 1). Electricity production at Nesjavellir Geothermal Power Plant started in 1998. In October 2006 the Hellisheidi Geothermal Power Plant started operation. At first there was a 90 MW electricity production, in 2007 a 30 MW low-pressure turbine was brought into use. In fall 2008 the electricity production was increased with two 40-45 MW turbine units. Hot water production is planned to start in 2010.

In Figure 2 the concentration of hydrogen sulfide measured at Grensasvegur measuring station in Reykjavik from January 1st to May 1st in 2007, 2008 and 2009 is plotted. These are 30 min averages. This time period is chosen because a high concentration is more common in the winter time than in summer and because the measurement device at Grensasvegur measuring station was out of order from May to August 2008. The figure shows that except for one major event in early February the peaks in the concentration seem to be lower in 2009 than in 2008 and 2007. Further comparison can be seen in Figure 3 where the data is plotted as a histogram of the hydrogen sulfide concentration in Reykjavik for the same periods. In Figure 4 incidences with concentrations higher than 100 µg/m^3 are shown larger. The highest concentration in the period in 2007 is about 190 µg/m^3 and 30 measurements yield more than 100 µg/m^3. The highest concentration measured in the period in 2008 is 186 µg/m^3 and 26 measurements show more than 100 µg/m^3. For the period in 2009 the highest concentration is 217 µg/m^3 and 41 measurements give more than 100 µg/m^3 (see Table 1).

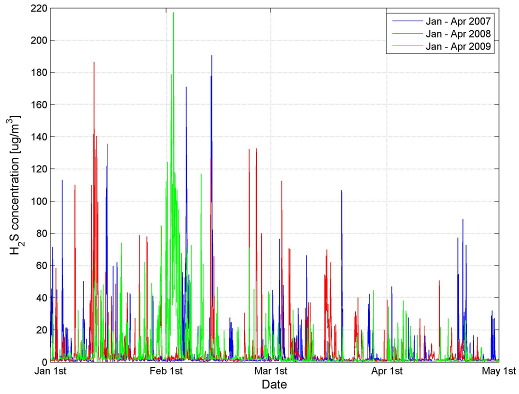

Figure 2. Measured hydrogen sulfide concentration at Grensasvegur measuring station in Reykjavik City from January 1st till May 1st 2007 (blue), 2008 (red) and 2009 (green).

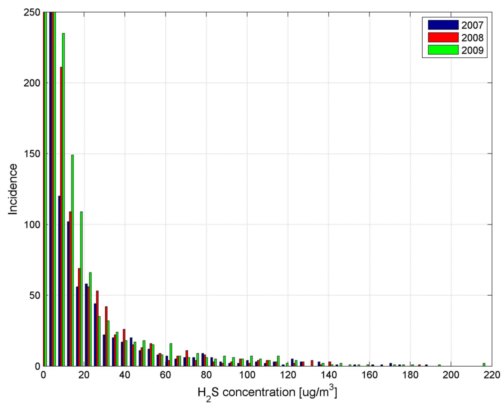

Figure 3. Histogram of measured 30 min hydrogen sulfide concentrations at Grensasvegur measuring station in Reykjavik City from January 1st to May 1st 2007 (blue), 2008 (red) and 2009 (green). Note that the plot is truncated at 250 incidents.

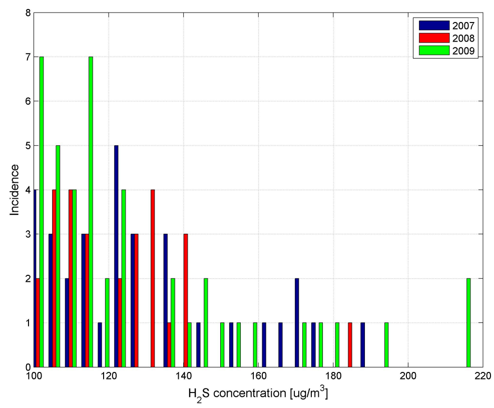

Figure 4. Histogram of measured 30 min hydrogen sulfide concentrations above 100 µg/m^3. Measurements from Grensasvegur measuring station in Reykjavik City from January 1st to May 1st 2007 (blue), 2008 (red) and 2009 (green). Note that the plot is scaled from 0 to 8 incidences.

Table 1. Number of 30 min averages of measured H_2S that are higher than 100 and 150 µg/m^3 and the highest value for each year 2007, 2008 and 2009, January 1st to May 1st.

Year	Number of 30 min H_2S measurements giving more than 100 (150) µg/m^3	Highest 30 min value of H_2S [µg/m^3]
2007	30 (7)	190
2008	26 (1)	186
2009	41 (8)	217

When Hellisheidi Power Plant was enlarged in the fall of 2008 the number of turbines was doubled and so the gas emissions were also roughly doubled. This could affect the hydrogen sulfide concentration in Reykjavik. Weather conditions can have a large influence on hydrogen sulfide concentrations. Therefore it is necessary to analyze the weather parameters such as wind direction, wind speed, precipitation and temperature to estimate the effects of weather on the hydrogen sulfide concentration.

When winds are from the east the concentration is more likely to rise in Reykjavik than if the wind is coming from other directions since the Nesjavellir and Hellisheidi Power Plants are located east of Reykjavik. In Figure 5 the incidence of easterly winds in Reykjavik is plotted for January 1st till May 1st 2007, 2008 and 2009. The data used here are 10 minute values of wind and the data is plotted in intervals of 5 degrees from 75° to 125°. Winds directly from the east are measured as 90° and the Nesjavellir Power Plant is located at 97 degrees with respect to the Grensasvegur measuring station and Hellisheidi Power Plant 116 degrees. Figure 5 shows that winds from 100° to 125° were more common in the observation period in 2009 than in 2007 and 2008. This means that winds from the direction of Hellisheidi were more common in the 2009 period. Also since the Hellisheidi Power Plant enlargement is detected in the 2009 period one might not be surprised that the highest concentration in this comparison is in 2009. Most 30 min values over 100 µg/m^3 are also in 2009.

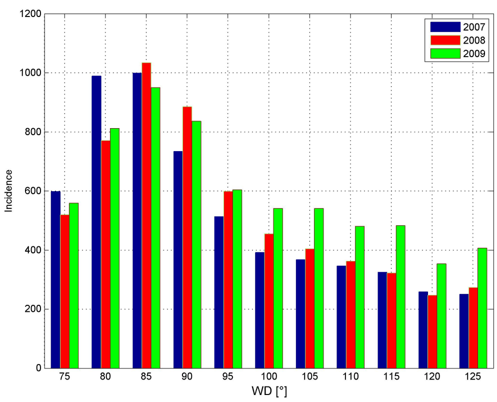

Figure 5. Histogram of easterly wind direction observed in Reykjavik City from January 1st to April 1st 2007 (blue), 2008 (red) and 2009 (green).

3. COMPARISON OF EVENTS

The analysis of the measured data in the previous section shows that high hydrogen sulfide concentration is event driven, that is, most of the time the concentration is low or zero but during certain weather condition the concentration rises. To analyze which weather conditions are favorable for high concentrations a search was performed in calm winds from the east, the direction of the power plants. Three events were identified and analyzed. Weather measurements from Reykjavik are carried out at the Icelandic Meteorological Office at Bustadarvegur in Reykjavik and the weather station in Middalsheidi highlands which is located between the power plants and Reykjavik. The locations of the weather stations are shown in Figure 1.

In the next three subsections the events are discussed and then a comparison is made.

3.1 February 1st – 4th 2009 (Feb. ’09 event)

During the first four days of February 2009 high hydrogen sulfide concentrations were observed at the Grensasvegur measuring station in Reykjavik and the concentration on February 2nd was one of the highest on record as is shown in Figure 6. At a measuring station located in Kopavogur town (see Figure 1) even higher concentration were observed than at Grensasvegur as is shown in Figure 7. The highest recorded peak was over 350 µg/m^3 and the highest 24-hr. mean concentration at the Kopavogur station was 150 µg/m^3 which is equal to the health limit given by WHO. In Figure 8 the wind direction during this period is shown, both in Reykjavik and Middalsheidi highlands which is located east of Reykjavik, between the city and the power plants. The wind direction during this period was very stable, around 100° in Reykjavik and around 70° at Middalsheidi. Figure 9 shows the wind speed at Reykavik and Middalsheidi. The wind speed in Reykjavik is low and steady, always below 4 m/s. At Middalsheidi the wind speed is higher, mostly in the range 4-8 m/s. In Figure 10 the temperatures in Reykjavik and Middalsheidi highlands are compared. Temperatures were in the range 0 to -5°C for the whole period in Reykjavik, and slightly lower at Middalsheidi but highly correlated to those in Reykjavik. No significant precipitation was measured.

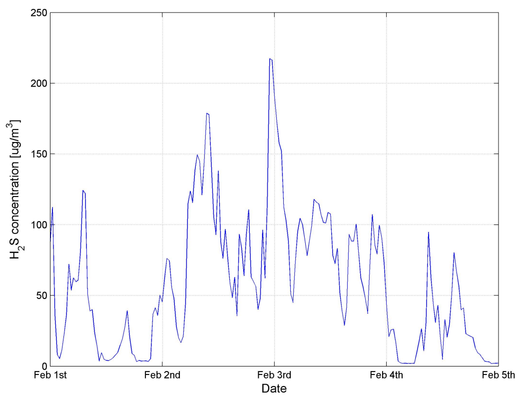

Figure 6. Measured hydrogen sulfide concentrations at Grensasvegur measuring station during the Feb. ’09 event.

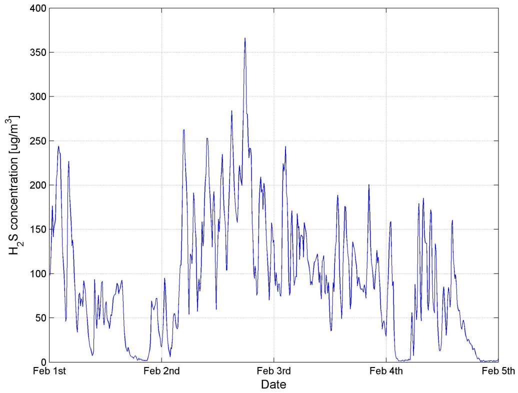

Figure 7. Measured hydrogen sulfide concentrations at Kopavogur measuring station during the Feb. ’09 event. Notice that the scale is different from Figure 6.

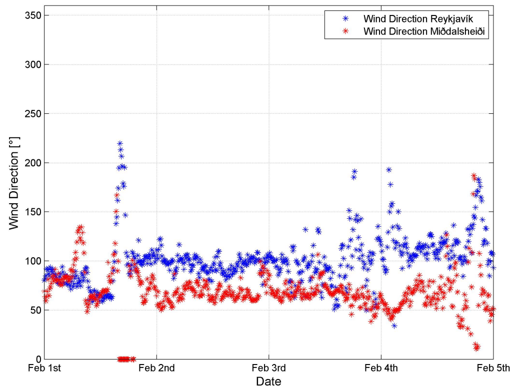

Figure 8. Wind direction in Reykjavik (blue) and at Middalsheidi highlands (red) during the Feb. ’09 event.

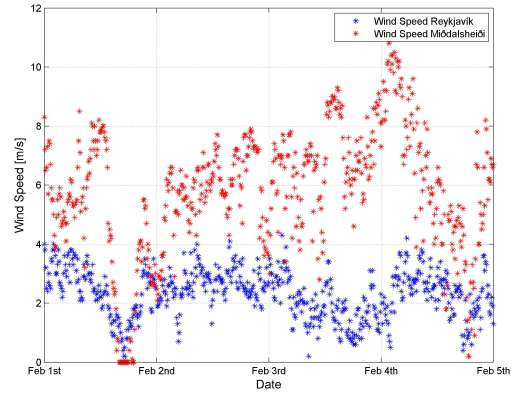

Figure 9. Wind speed in Reykjavik (blue) and at Middalsheidi highlands (red) during the Feb. ’09 event.

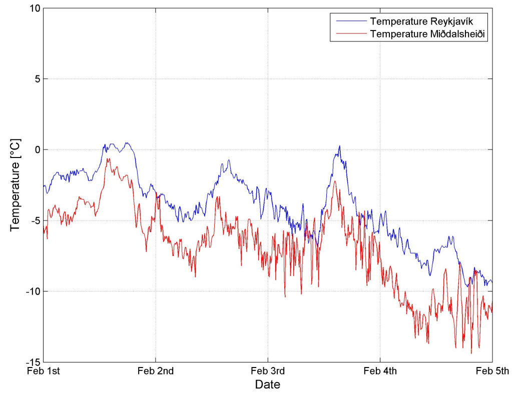

Figure 10. Temperature in Reykjavik (blue) and at Middalsheidi highlands (red) during the Feb. ’09 event.

3.2 January 11th – 13th 2008 (Jan. ’08)

From January 11th to January 13th 2008 the hydrogen sulfide concentration at Grensasvegur measuring station rose to rather high concentrations. The concentration signal is rather peaky, with three distinctive peaks the longest one on January 12th (see Figure 11). Figure 12 shows the wind direction during the event and it is remarkably similar to that of the Feb. ’09 event, steady through the period, although it may be argued that the wind direction is slightly more unstable in Reykjavik during this event than during the Feb. ’09 event. Figure 13 shows the wind speed and it is also comparable to that of the Feb. ’09 event. The temperature is slightly higher in the Jan. ’08 (see Figure 14) event than in the Feb. ’09 event. No precipitation was detected during this period.

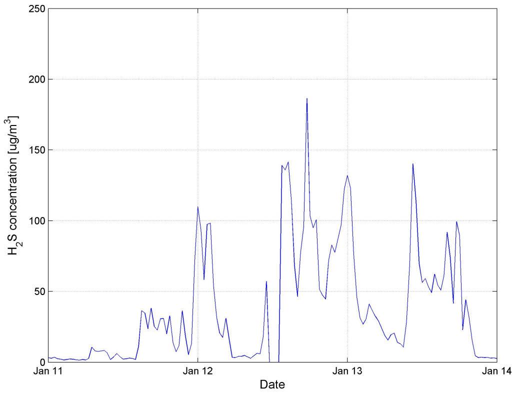

Figure 11. Measured hydrogen sulfide concentration at Grensasvegur measuring station during the Jan. ’08 event.

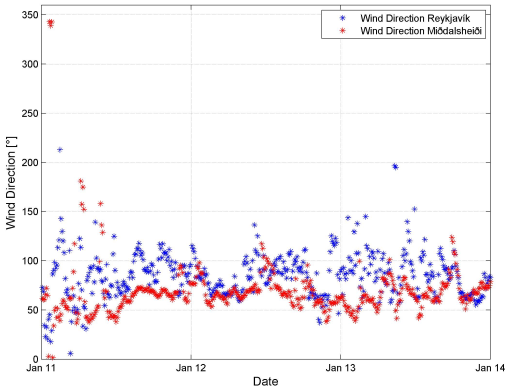

Figure 12. Wind direction in Reykjavik (blue) and at Middalsheidi highlands (red) during the Jan. '08 event.

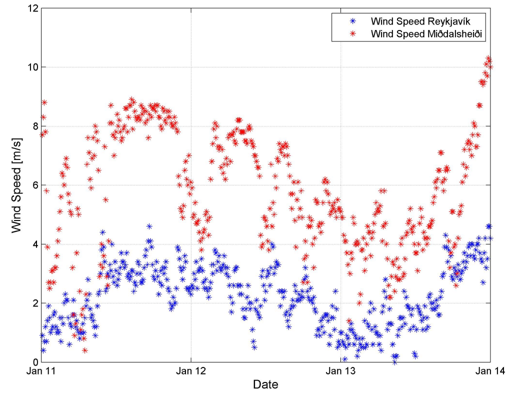

Figure 13. Wind speed in Reykjavik (blue) and at Middalsheidi highlands (red) during the Jan. '08 event.

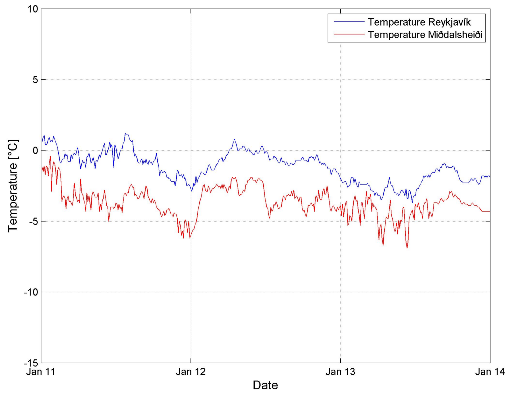

Figure 14. Temperature in Reykjavik (blue) and at Middalsheidi highlands (red) during the Jan. '08 event.

3.3 October 9th – 11th 2007 (Oct. '07)

The third event analyzed took place during October 9th - 11th, 2007. The concentration measured at the Grensasvegur measuring station is very different from the other periods as shown in Figure 15. The concentration is consistently low and never exceeds 15 µg/m³. Figure 15 shows the wind direction at the weather stations. The wind is from the east both in Reykjavik and on Middalsheidi highlands during Oct. 9th and 10th, similar to the other two events. On the 11th the wind turned to the north in the early morning but back to the east around noon. Figure 17 shows that on October 9th the wind speed was low but increased on the 10th and reached 10 m/s in Reykjavik and about 18 m/s in the Middalsheidi highlands. Late at night on the 10th and in the early morning on the 11th the wind speed had decreased but increased again during October 11th. It is clear that the wind conditions were similar on the 9th and partly on the 10th as during the previous two events but then the wind speed increased significantly although the wind direction remained unchanged. Figure 18 shows the temperature in Reykjavik during this period. It ranged from 5 to about 12 °C but the temperature on Middalsheidi highlands was about 3 °C lower. During this event there was some precipitation which is shown in Figure 19. There was some precipitation in the morning on the 9th and in the early morning on the 10th and then in the evening on the 11th.

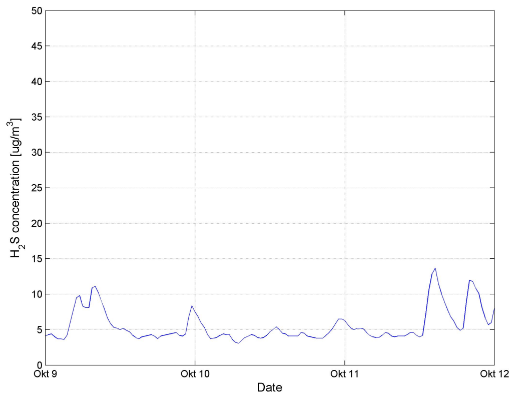

Figure 15. Measured hydrogen sulfide concentration at Grensasvegur measuring station during the Oct. '07 event.

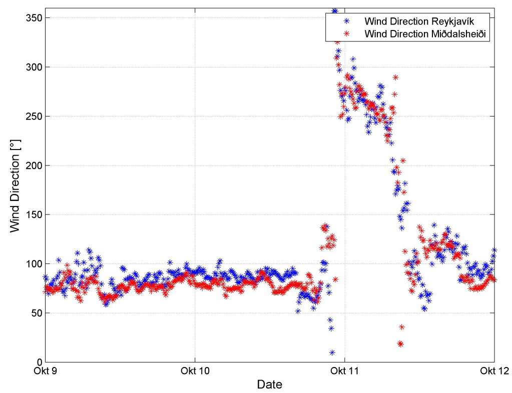

Figure 16. Wind direction in Reykjavik (blue) and at Middalsheidi highlands (red) during the Oct. '07 event.

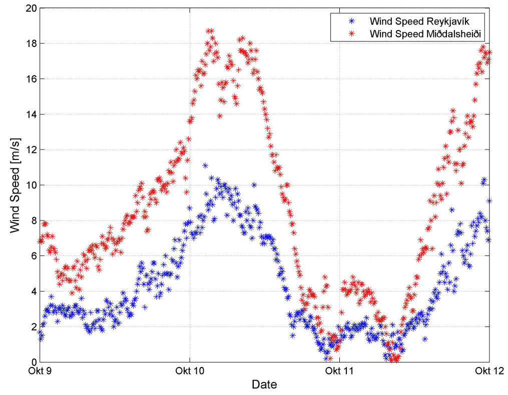

Figure 17. Wind speed in Reykjavik (blue) and Middalsheidi highlands (red) during the Oct. ’07 event.

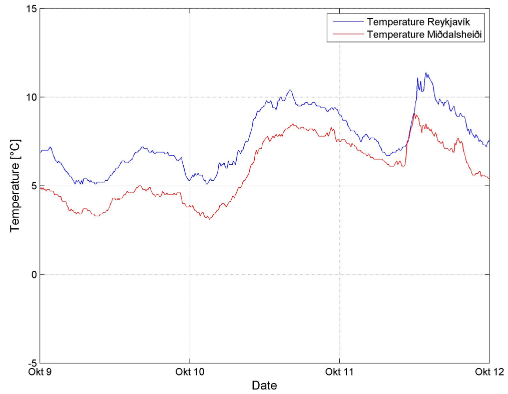

Figure 18. Temperature in Reykjavik (blue) and Middalsheidi highlands (red) during the Oct. ’07 event.

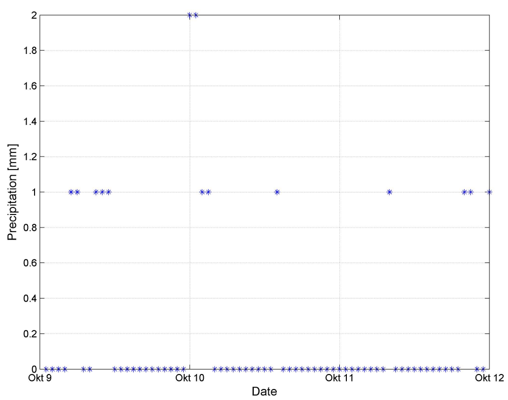

Figure 19. Precipitation in Reykjavik during the Oct. ’07 event.

3.4 Comparison

The three events, discussed in previous sections, that were found for the measuring period 2007-2009 with steady wind from east, indicate the importance of the weather condition on hydrogen sulfide concentration.

During all events the wind direction was similar, that is, from the east although during the Oct. ’07 event the wind direction changed to a different direction for a few hours. During the Feb. ’09 and Jan. ’08 events the wind speeds were low in Reykjavik and up to 10 m/s in Middalsheidi highlands. During the Oct. ’07 event the wind speed was low early on Oct. 9th and Oct. 11th but higher on Oct. 10th and late Oct. 11th. Temperatures varied between the events. During the Jan. ’08 and Oct. ’07 events the temperatures were stable around 0°C and around 8 °C in Reykjavik, respectively. During the Feb. ’09 event the temperature decreased from about -2 °C to -10 °C in Reykjavik. There was no precipitation during the Feb. ’09 and Jan. ’08 events but some during the Oct. ’07 event.

The concentrations during the Feb. ’09 and Jan. ’08 events were much higher than during the Oct. ’07 event, when the concentration was mostly around 5 µg/m^3. The difference between the Feb. ’09 and Jan. ’08 concentrations is mainly that in Feb. ’09 the concentration stayed high for a longer period while the Jan. ’08 concentration was peakier.

The Feb. ’09 and Jan. ’08 events are very similar both in weather and concentrations. The Feb. ’09 event was the highest measured event on record. The WHO health limit was reached in Kopavogur and Nordlingaholt which is a district on the far-East side of the Reykjavik district (where test measurements were made at the time). The weather factors that are ideal for high concentrations in the Reykjavik area are winds from the East, cold weather, low wind speed and no precipitation. These were the weather conditions during the Feb. ’09 and Jan. ’08 events. The weather conditions in Oct. ’07 were quite different, with higher temperature, varying wind speed and precipitation. The frequency of the ideal weather conditions for high H_2S concentration in Reykjavik could give an indication of how often high concentration should be expected in Reykjavik and how often they might have gone undetected. More data analyses are underway to detect which weather factor influences the concentration the most.

4. DISTRIBUTION OUTSIDE REYKJAVIK AREA

A measurement program is being executed to measure hydrogen sulfide concentration at point locations around Nesjavellir and Hellisheidi Power Plants. These measurements are performed with a hand held measuring device (Jerome 631-X). The measurements are taken during a trip lasting few hours, depending on weather conditions, repeated for four days in a row. On the morning of a measuring day the wind direction is observed and that determines where the measurements are performed. The measurements are performed in a segment some distance from the power plants at the locations where hydrogen sulfide can first be detected until the concentration has dropped to zero again. The area used for the measurements (see Figure 1) is a circle drawn from Reykjavik through Mosfellsbær to Þingvallavatn, around Lake Þingvallavatn and to the south on the east side of the lake to the Town of Selfoss, then down to Eyrarbakki and that way up to Hellisheidi power plant and to Reykjavik. Depending on the distance travelled (which depends on the distribution of hydrogen sulfide) the measurements take about 3 to 5 hours. These measurements will be taken during the course of one year and by doing so the summer and winter values can be compared. Also since the measurements are performed for a few days in a row a comparison can be made between days with similar but not identical weather.

This program is underway and the results are still being analyzed. In the following section, an example of measurements from two days in March 2009 is discussed.

4.1 Comparison between two measuring days

On March 24th and 25th, 2009, the winds were from the north and northeast so that hydrogen sulfide measurements were made from Reykjavik City to the Town of Selfoss (see Figure 1). The measuring sites are shown in

Figure 20 and 21 with pink circles. On the 24th the highest concentration was about 140 µg/m^3 close to Hellisheidi Power Plant. Farther south from the plant the highest concentration was about 51 µg/m^3 (about 12 km from the plant). The second highest concentration farther from the power plant was about 16 km southwest from Hellisheidi Power Plant. A little west of the second highest concentration measurement a lower concentration was observed although this location was in a straight line from the power plant and the highest concentration.. This indicates fluctuations in the plume (see

Figure 20). During the measuring time the winds were from the north and north-northeast (about 0° - 30°). Wind speeds range from 7 to 10 m/s in the highlands.

On March 25th, the highest concentration measured is at Hellisheidi Highlands, 91 µg/m^3 (see Figure 21). The hydrogen sulfide concentration was more diffuse than the day before. Two different highs in the concentration are seen in Figure 21, one at Hellisheidi Highlands and one closer to Reykjavik City. Since the winds were almost stable from the northeast, during the measuring time, this indicates two different sources.

There are slight weather differences between the two days. The wind direction had changed only slightly but the wind speed was much lower the second day and temperatures are also lower. The difference in hydrogen sulfide concentration is that on March 25th hydrogen sulfide was more widely distributed. This is possibly due to lower wind speeds that allowed the hydrogen sulfide to spread more widely in the crosswind direction.

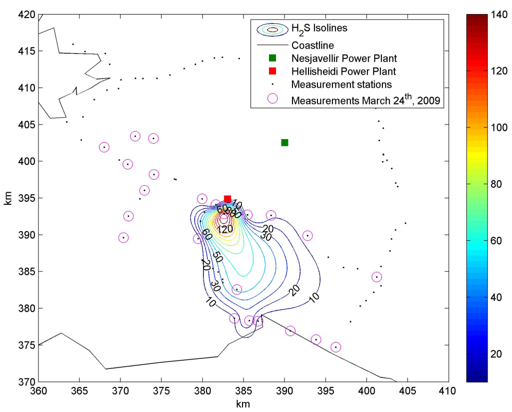

Figure 20. Contour plot of hydrogen sulfide concentration on March 24th 2009. Black dots are measurement spots used, the pink circled ones are the ones measured this particular measuring day. Green and red squares represent Nesjavellir and Hellisheidi Power Plant respectively. The axes have the ISN93 coordinates in km.

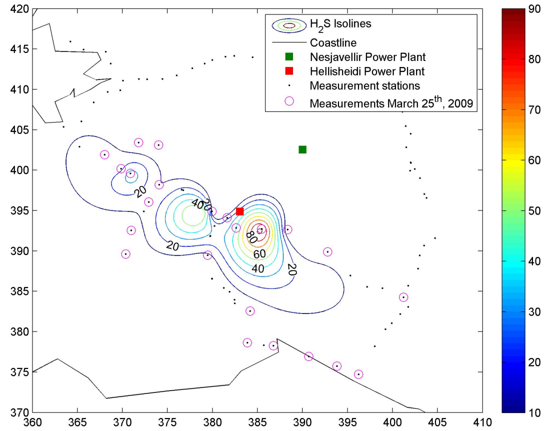

Figure 21. Contour plot of hydrogen sulfide concentration on March 25th 2009. Black dots are measurement locations used; the pink circled ones were used this particular measuring day. Green and red squares represent Nesjavellir and Hellisheidi Power Plant respectively. The axes have the ISN93 coordinates in km.

5. CONCLUSIONS

Hydrogen sulfide emission close to Reykjavik City has increased the least few years with growing geothermal power production. Preliminary analysis of measurements, both at fixed locations as well as at variable point locations, indicates strong influence of weather conditions on magnitude and frequency of raised hydrogen sulfide concentrations. Comparing events it seems that low wind speed, with cold air and little or no precipitation are conducive to high hydrogen sulfide concentrations in Reykjavik. Further analysis and measurements are underway to investigate which parameters exert most influence on the concentration. Preliminary results from measurements outside the capital area indicate that the hydrogen sulfide is more widely distributed at lower wind speeds.

ACKNOWLEDGEMENTS

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