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An evaluation of ambient sulphur dioxide concentrations from passive degassing of the Sulphur Springs, Saint Lucia geothermal system: Implications for human health

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ABSTRACT

Sulphur Springs Park in Saint Lucia is a site of energetic geothermal activity associated with the potentially active Soufrière Volcanic Centre. The Park is one of Saint Lucia's most important tourist attractions, and is marketed as the 'world's only drive-in volcano'. It has an on-site staff of tour guides and vendors, as well as over 200,000 visitors annually. There are also a number of residents living in the areas bordering the Park. Recreational use is made of the geothermal waters for bathing, application of mud masques, and in some cases drinking. As part of the University of the West Indies, Seismic Research Centre's (UWI-SRC's) overall volcano monitoring programme for Saint Lucia, the volcanic emissions at Sulphur Springs (hot springs, mud pools and fumaroles) have been regularly monitored since 2001. In recent years, visitors, staff, and management at the Park have expressed concern about the health effects of exposure to volcanic emissions from the hydrothermal system. In response to this, SRC has expanded its regular geothermal monitoring programme to include a preliminary evaluation of ambient sulphur dioxide (SO_2) concentrations in and around the Park, to assess the possible implications for human health.

Passive diffusion tubes were used to measure the atmospheric SO_2 concentrations at various sites in Sulphur Springs Park (SSP), in the town of Soufrière and in the capital of Castries. Measurements of average monthly ambient SO_2 with the passive samplers indicated that during the dry season period of April to July 2014 concentration at sites closest to the main vents at SSP (Group 1), which are routinely used by staff and visitors, frequently exceeded the WHO 10-minute AQG for SO_2 of 500 μg/m^3. However, for sites that were more distal to the main venting area (Groups 2 and 3), the average monthly ambient SO_2 did not exceed the WHO 10-minute AQG for SO_2 of 500 μg/m^3 during the entire monitoring period. The measured concentrations and dispersion patterns of ambient SO_2 at SSP appear to be influenced by rainfall, proximity to the fumarolic vents, altitude (local topography), local atmospheric circulation and plume dispersion, and anthropogenic sources. Brochures and posters were prepared, for public distribution and display, on possible gas hazards that may be encountered at SSP and precautionary measures that may be taken by visitors to help minimise potential risk from elevated exposure to volcanic gases.

1. Introduction

It has been unequivocally demonstrated that gases and aerosols from eruptive and non-eruptive volcanic and geothermal activity can adversely affect human health and the environment (Baxter, 2000; Aiuppa et al., 2001, 2003; Delmelle et al., 2002; Zhang et al., 2008; D'Alessandro et al., 2013). Volcanic emissions common from volcanoes and geothermal areas can be vented from the main crater area, from fumarolic fields, or diffusely through soil (Hansell et al., 2007). Volcanogenic air pollutants known to cause the most serious impact on human health are carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen chloride (HCl) and hydrogen fluoride (HF). Other contributors include carbon monoxide (CO), hydrogen sulphide (H_2S), radon (Rn), mercury (Hg) and other volatile trace elements. Similar to anthropogenic point source emissions, the extent to which these gases impact the proximal and distal environment depends on several factors. Once in the atmosphere, the gases are affected by physical and chemical processes (gas-phase reactions, reactions on, in, or with suspended solid and liquid particles), which may lead to their rapid or slow deposition, and favour or delay their conversion to aerosols. The sensitivity of the soil and vegetation receptors to volcanogenic pollution is of necessity, also an important factor. Clearly, a proper assessment of the environmental effects of volcanic gases requires multidisciplinary and time-integrated research. Such studies are important because they increase our ability to forecast and mitigate volcanic gas hazards.

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The main hazards from volcanic gases are respiratory related, with human health effects from volcanogenic pollution varying in the degree of severity; covering a range of minor effects to serious illness such as impaired pulmonary function as well as premature death in certain cases (Bhugwant et al., 2009). Volcanic gas has a particularly strong tendency to increase the environmental concentration of SO_2 significantly, as was shown for Mount Oyama in Miyakejima in Japan (Iwasawa et al., 2009). SO_2 poses a significant environmental and occupational exposure concern due to the risk of adverse health effects. A small number of deaths of visitors to volcanic areas have been reported in different parts of the world following exposures to SO_2 (particularly in those with pre-existing respiratory disease such as asthma) and H_2S (Hansell and Oppenheimer, 2004; Witham, 2005; Hansell et al., 2007).

Through collaboration with the Soufrière Regional Development Foundation (SRDF) i.e. management of the Sulphur Springs Park (SSP), and the National Emergency Management Organisation (NEMO) of Saint Lucia, the University of the West Indies, Seismic Research Centre (SRC) established a volcanic SO_2 emissions monitoring network in and around the main volcano-hydrothermal area in Saint Lucia. The primary site, Sulphur Springs Park has a very high recreational value with >200,000 visitors annually and a complement of full-time tour guides on site; while the adjacent secondary site, the town of Soufrière, has >8400 residents. In an effort to improve and expand the SRC's capacity to provide volcanic surveillance, a novel monitoring network for quantifying the ambient concentrations of SO_2 was implemented using passive diffusion tubes at both sites. This approach could potentially serve as a model for SO_2 emissions monitoring networks for other volcanic islands in the Lesser Antilles.

The overall aims of this study were to quantify the atmospheric concentrations and dispersion pattern of volcanogenic SO_2 at Sulphur Springs, Saint Lucia measured for the first time with passive diffusion samplers; and to report on the potential health risks on three groups of individuals including Park workers, tourists, and residents living in the area surrounding the Park, resulting from exposure to the hydrothermal SO_2 emissions from Sulphur Springs. This information was then used to prepare public education materials to help guide persons visiting the area on preventative measures that they may adopt to help reduce their risks to unsafe exposure; as well as aid local stakeholders in the understanding and management of the possible health risks to the staff of Sulphur Springs and nearby residents.

2. Areas under investigation: Sulphur Springs Park and Soufrière

Saint Lucia experiences one wet and one dry season annually. The wet (rainy) season runs roughly from June to December and the dry season from February to May. January is a transition month and may be wet or dry. Average total annual rainfall is about 1700 mm with September usually being the rainiest month. Ambient air temperature in open spaces rarely reaches above 34 °C or falls below 22 °C. Winds are generally out of the east between 070° and 100° from true north, at an average speed of about 6 m.p.h. The windiest months are typically from January to July.

Sulphur Springs is the surface manifestation of a sub-surface geothermal field. The main area of the Sulphur Springs geothermal field is comprised of numerous hot springs, bubbling mud pools, boiling springs, and fumaroles in an area of strongly argillic altered rock approximately 200 m × 100 m in size (Fig. 1). Many fumaroles have temperatures of up to 100 °C or hotter, with temperatures of up to 172 °C being recorded on occasion (Lindsay et al., 2005). There is an extensive area of hydrothermally altered ground together with stunted vegetation on the flanks of Terre Blanche, indicating that this area was once geothermally active. The gases are of typical arc-type composition, with N_2 excess and low He and Ar content, with a dry gas composition dominated by CO_2 (ranging from 601 to 993 mmol/mol), with deeper magmatic sourced H_2S-rich vapour undergoing boiling and redox changes in the geothermal reservoir to emerge with a hydrothermal signature in the fumarolic gases (Joseph et al., 2013). The geochemistry of the thermal waters at Sulphur Springs is mainly of acid-sulphate type compositions (SO_4 = 78–4008 mg/L; pH = 3–7), and are of primarily meteoric origin (Joseph et al., 2013). Reservoir temperatures calculated from the evaluation of gas equilibria in the CO_2–CH_4–H_2 system reveal temperatures of 190 to 300 °C (Joseph et al., 2013).

Sulphur Springs is an important tourist destination for Saint Lucia, with several viewing platforms around the main venting area, with tour guides accompanying individuals or groups around the Park as well as several hot pools developed for recreational use. The time spent by visitors at the Park varies from minutes up to 2 h; with many opting to finish their visit with a soak in the recreational baths within the Park. The public and guides may be exposed to sulphur dioxide concentrations that are higher than typical outdoor air levels. The effects of exposure to any hazardous substance depend on the dose, the duration, the way one may be exposed, and their personal traits and habits. Vehicular traffic through the main area of the Park is limited, with parking for visitors generally available around the main entrance area.

The town of Soufrière is situated on the west coast of Saint Lucia, ~2 km away from Sulphur Springs, with the Pitons lying south of the town (Fig. 1). The characteristic "rotten egg" smell of hydrogen sulphide is occasionally observed by residents and visitors in the town, as local wind patterns direct the gas emissions from Sulphur Springs across the town. There is no significant industrial manufacturing activity in the town, and most businesses are centred on tourism, agriculture and fishing. The sampling site chosen in the town of Soufrière was the Soufrière Secondary Comprehensive School, which was on the outskirts of the business district. Castries, the capital of Saint Lucia, was chosen as a control site as it is situated in the north of the island, away from the volcano-hydrothermal system. In 2010, an estimated population of ~67,700, approximately one third of the islands population resided in the area. It has a sheltered harbour which receives cargo vessels, ferry boats, and cruise ships. Manufacturing activities in the city include food and beverages, condiments, corrugated cardboard cartons, handicraft, sporting goods, furniture, metal sheeting, apparel and souvenir items, among others. The city is well served by a bus system and taxi service.

3. Air quality guidelines for ambient SO_2 concentrations and exposure standards

The study of health hazards related to the monitoring of volcanic aerosols to quantify the exposure of populations to potentially harmful emissions is an emerging field with studies being conducted at several volcanic areas such as the Soufrière Hills Volcano, Montserrat and Rotorua City, New Zealand (Oppenheimer and McGonigle, 2004; Horwell et al., 2005; Heggie, 2009). However, investigations into the impact of volcanic emissions on health have been almost exclusively focused on acute responses, or the effects of one-off eruptions (Horwell and Baxter, 2006; Bhugwant et al., 2009). With the increasing interest in the impact of the effects of passive volcanic emissions on human health, the International Volcanic Health Hazard Network (IVHHN) was launched in 2003 as an umbrella organisation for all research and information on volcanic health hazards. IVHHN has compiled a review of international guidelines for monitoring health hazards associated with volcanic activity due to gas emissions. These guidelines were primarily applied in major economies to the regulation of air pollution in populated areas, as well as to the safety of workers, from industrial sources, as sulphur dioxide is a by-product of, or used in, numerous industrial processes, as well as contaminating urban air from traffic engine combustion in vehicles using petrol/gasoline with raised sulphur levels. However, as they are primarily health standards based on the chemical properties of SO_2 itself, the standards are just as applicable in a volcanic setting. There is a tremendous range in ambient SO_2 guidelines that exist internationally. The range of guideline values for each averaging period for SO_2 exposure guidelines from various international sources are summarised in Table 1 (IVHHN, 2014). Differences

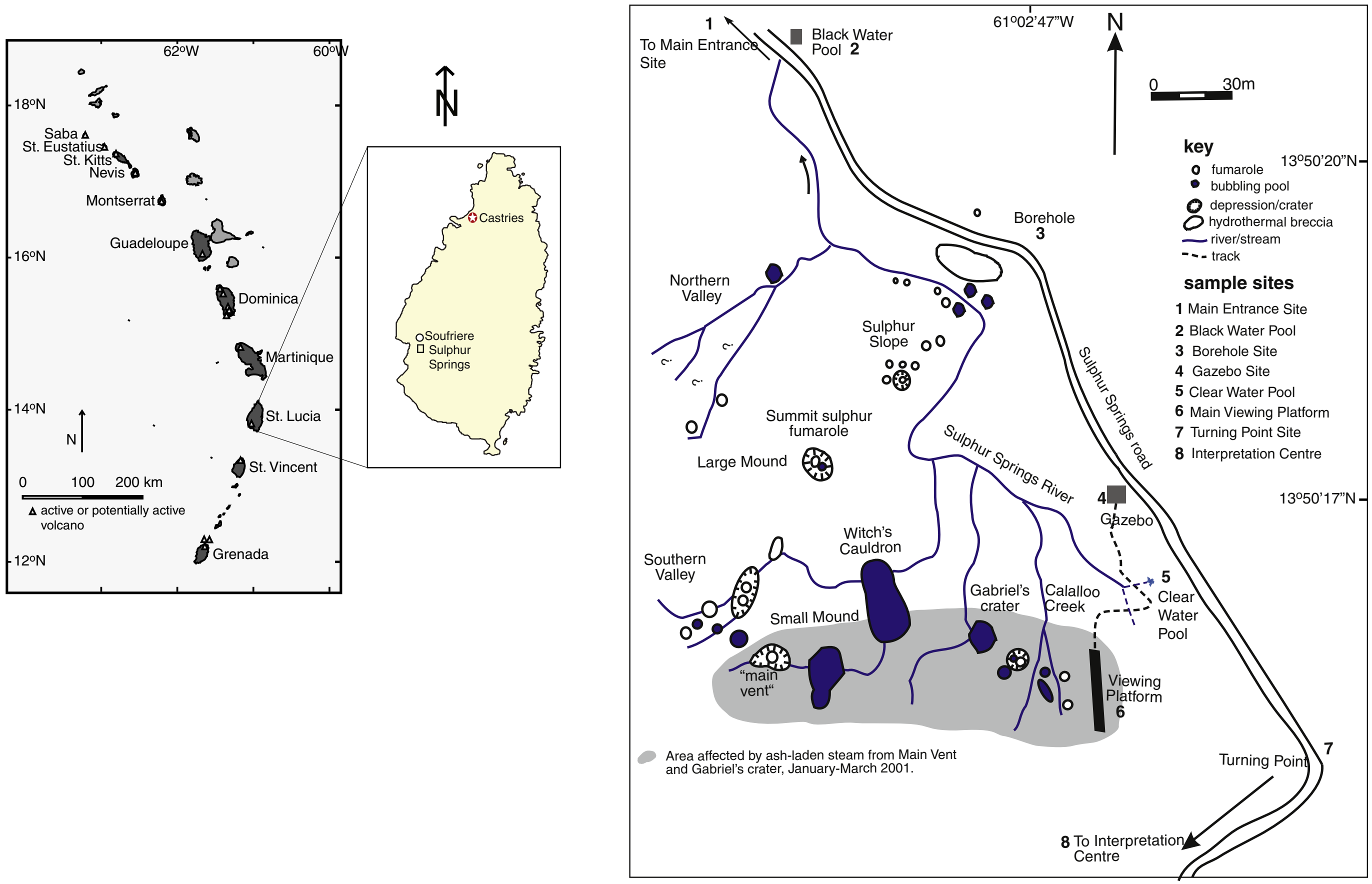

Fig. 1. Map of Lesser Antilles showing the location of Saint Lucia (left), and map of Sulphur Springs Park showing the names and locations of sampling sites (right).

Table 1
Summary of the ranges of ambient SO_2 guideline levels.

Averaging period	Min (μg/m^3)	Max (μg/m^3)
10–15 min	267	459
1 h	149	2620
24 h	50	401
Annual	21	100

Table adapted from IVHHN Volcanic Gas Guidelines for Emergency Managers and Scientists: http://www.ivhhn.org/index.php?option=com_content&view=article&id=82.
Averaging times for guidelines range from 10 minutes (WHO) to annual.

between countries' guidelines may be explained by the age of the guideline, the practical achievement of a standard based on current and predicted pollution levels, or the data from which the standard was set (e.g. epidemiological study versus actual pollution levels). Averaging times for guidelines range from minutes to annual. It may therefore be beneficial for the volcanological community to come to a common approach and issue guidance, based on what IVHHN has already compiled, to specifically address the potential health hazards associated with volcano tourism.

In the case of Miyakejima Island, where the Oyama volcano erupted in June 2000 and still periodically emits large amounts of SO_2, the Japanese authorities have gone further than any other group in setting the agenda for the protection of residents and visitors from unsafe ambient concentrations of volcanic gases. Some of the measures adopted include the carrying of gas masks at all times; the implementation of a system of alarm when sulphur dioxide levels get too high; as well as air filters on or inside sensitive buildings (Iwasawa et al., 2015).

With reference to the three groups of individuals exposed to volcanic SO_2 from Sulphur Springs, the potential risks to visitors and nearby residents are assessed using the World Health Organization (WHO) air quality guideline (AQG) for maximum exposure limit of SO_2 at 500 μg/m^3 for 10 min (WHO, 2006). This guideline is aimed at protecting the most susceptible (asthma sufferers) in the population to the effects of the gas. It is also very applicable to individuals with other chronic lung diseases. For the assessment of the potential risks to the staff at SSP, guidelines provided by the National Institute for Occupational Safety and Health (NIOSH) of the United States are chosen. The NIOSH guidelines, while used primarily for industrial workers, state that for SO_2 concentrations of 2 ppm over 8 hour exposure (TWA), as well as a short term exposure limit (STEL) of 5 ppm over 15 min is recommended. In general these higher values, as compared to those used for visitors and nearby residents, are thought to be permissible as the risk to workers is allowed to be higher than in the general population because they are usually fitter and have more options for controlling their exposure than people living in the community who include the sick, children and the elderly.

4. SO_2 sampling and measurements

From March to December 2014, SO_2 concentrations were measured using passive diffusion samplers at 8 sites around the Sulphur Springs Park (Fig. 1), at 1 site in the town of Soufrière, and at 1 site in the town of Castries (northern Saint Lucia) away from the geothermal emissions. The locations of the sites chosen at SSP were based on their proximity to the main venting areas of the geothermal field, as well as the areas most frequented by visitors and staff.

4.1. SO_2 measurement using passive diffusion samplers

At each of the 10 sampling sites, the passive diffusion SO_2 gas samplers (e.g. Delmelle et al., 2002) supplied by Gradko Environmental (accredited by the United Kingdom Accreditation Service), were exposed for a 4-week period, and used to provide a quantitative SO_2 measurement based on time-integrated concentrations during the exposure period. This method is therefore not capable of providing information on periodic variations/spikes in SO_2 concentrations that may be above the WHO 10-min AQG during the 4-week measuring period. Hence, periodically high concentrations that exceed the AQG, which are hazardous to human health, are likely to be interspersed with lower ones and will be masked by the overall low monthly mean. Sites were selected to provide information on the spatial variability in ambient SO_2 levels around the Park as well as in areas where staff and visitors tend to congregate, and were located in open areas as much as possible and away from other sources of SO_2, such as vehicular traffic. The passive diffusion gas sampler is based on the property of molecular diffusion of gases and species-specific collection on an impregnated filter specific to the SO_2 pollutant measured. The quality of the SO_2 concentrations measured by passive samplers, has been tested and validated by other international research studies in urban and volcanic environments (Delmelle et al., 2002; Bhugwant et al., 2009; D'Alessandro et al., 2013), as well as tested in different tropical and subtropical regions (Carmichaël et al., 1996; Ferm and Rodhe, 1997; Murrell et al., 2014).

The tubes were deployed in triplicate at each site, and mounted 1.5–2.5 m above the ground in areas of unrestricted air circulation, with no over-hanging vegetation or obstructions. After being exposed for the 4 week period, the tubes were collected and enclosed in plastic storage vials. Each batch of diffusion tubes and a travel blank (tube that was carried in the field but not exposed) were stored in the refrigerator at 4 °C for up to 5 days, before being sent to Gradko for subsequent analysis by ion chromatography in order to calculate the SO_2 concentrations. The detection limit of the method over a 4 week exposure period was 0.04 μg S. The precision of the tubes, expressed as the coefficient of variation (CV) of the tubes, was $<$20% for all of the exposure periods.

4.2. SO_2 measurement using a ToxiRAE monitor

The passive samplers do not allow for comparison of ambient SO_2 concentration against NIOSH guidelines as the results are recorded as monthly averages, and not continuous measurements. To obtain some continuous measurements of ambient SO_2 concentrations, a ToxiRAE Pro monitor (Model G02-B310-100) equipped with an SO_2 sensor, was periodically used to obtain readings at the Main Viewing Point (MVP) in the Park. The ToxiRAE monitor is a personal, wireless monitor for toxic gases and oxygen that is widely used in industrial settings and by first responders, to provide real-time monitoring of gas concentrations. The monitor was exposed for periods that varied from 1 to 3 h, and was co-located with the passive diffusion tubes at the MVP. Data was logged at 1 minute intervals, and real-time readings of short-term exposure limits (STEL) for 15 minute intervals, time-weighted average (TWA) over an 8 hour period, and peak gas concentrations were provided. The electrochemical SO_2 sensor had a detection range of 0 to 20 ppm at a 0.1 ppm resolution, with a factory calibrated accuracy of $\pm$10% or 0.3 ppm, whichever is greater.

5. Results

5.1. Passive diffusion samplers

Meteorological data from the Hewanorra International Airport in the south of Saint Lucia for the period March–December 2014 is presented in Table 2, with the rainy season indicated by increased rainfall during the period July to November 2014. The average monthly SO_2 concentrations for all sites monitored for the period April to December 2014 are summarised in Table 3, and graphically displayed in Figs. 2a & b. For the entire monitoring period it was observed that there were three general groupings of sites based on monthly SO_2 concentrations recorded. Group 1 consisted of the sites BWP, BHS, GSS, MVP, and CWP, which were all within the main area of the Park, closest to the fumarolic vents. This group of sites recorded the highest average SO_2 concentrations in the range of ~177–943 μg/m^3 (Fig. 2a). Group 2 sites comprised

Table 2
Meteorological data from the Hewanorra International Airport in the south of Saint Lucia for the period March–December 2014.

Month	Wind direction (°s from true North)	Wind speed (knots)	Average Temperature (°C)	Average rainfall (mm)	Relative humidity (%)	Average hours of sunshine
March	88.2	15.36	26.4	38.0	73	8.5
April	95.5	16.08	27.2	40.7	73	10.0
May	93.2	15.32	27.6	25.0	74	9.4
June	90.3	17.16	28.3	65.2	76	8.5
July	89.6	16.14	28.1	107.0	77	8.9
August	91.8	13.41	28.0	164.6	81	7.8
September	92.3	11.77	28.3	169.7	79	8.8
October	92.1	9.36	28.1	154.9	80	8.4
November	89.2	14.38	27.8	245.4	80	8.4
December	80.6	12.36	27.2	21.8	76	9.8

of MES, TPS, and ICS, and were further away from the main area of the Park. They recorded lower average SO_2 concentrations in the range of ~0–200 μg/m^3 (Fig. 2a), with the exception of the October average for MES (Table 3). Group 3 consisted of the sites SCSS and CCS, which were completely outside of the Park; recorded the lowest average SO_2 concentrations in the range of 0–173 μg/m^3 (Fig. 2b and Table 3).

The range in average monthly SO_2 concentrations measured over the entire monitoring period per site is depicted in the box and whiskers plot shown in Fig. 3. It was observed that Group 1 sites exhibited larger ranges and higher SO_2 concentrations as compared to Groups 2 and 3 sites. Group 1 sites BHS and GSS also had the largest range in SO_2 concentrations over the monitored period, with concentrations of 395–779 μg/m^3 and 245–634 μg/m^3 respectively, fitting within the 25th and 75th percentiles of the dataset (Fig. 3). Group 2 sites ICS and TPS, had the smaller ranges in average SO_2 concentrations over the monitored period, with most of the data recorded fitting within the 25th and 75th percentiles (15–28 μg/m^3 and 84–100 μg/m^3 respectively) of the dataset (Fig. 3). The Group 2 site MES had higher average concentrations and a larger range in SO_2 concentrations (139–200 μg/m^3 fitting within the 25th and 75th percentiles) as compared to other Group 2 sites. Group 3 site SCSS had the smallest range in average SO_2 concentrations over the entire monitoring period, with concentrations of 1.2–2.8 μg/m^3 fitting within the 25th and 75th percentiles of the dataset.

Comparison of dry season and rainy season SO_2 measurements show that for Group 1 sites, higher monthly SO_2 concentrations were recorded during the dry season months of April to June, ranging from 438 to 943 μg/m^3, with the highest concentration of 943 μg/m^3 recorded at the BHS, in the month of May (Table 3). The average monthly SO_2 concentrations recorded in the rainy season months of July to November for Group 1 sites were in the range of 207–560 μg/m^3 (Table 3). Seasonal variability in SO_2 concentration was not particularly apparent for Groups 2 and 3 sites, as evidenced by their small ranges in average SO_2 concentrations throughout the entire monitoring period. MES recorded the highest average monthly SO_2 concentration for Group 2 sites, with a concentration of 316 μg/m^3 recorded in the month of October. CCS recorded the highest recorded average monthly SO_2 concentration for the Group 3 sites, with a concentration of 173 μg/m ^{3} recorded in August (Table 3).

5.2. Air quality and health guidelines

Comparison of the average monthly SO_2 concentrations recorded using the passive diffusion samplers at Groups 1 and 2 sites, with that of the WHO 10-minute AQG, for the dry and rainy seasons is displayed for sites within SSP in Figs. 4a & b respectively. The wind roses for the meteorological data recorded at the Hewanorra International Airport in the south of Saint Lucia, between April and December 2014, are also depicted in Figs. 4a & b. The prevailing wind direction is from the east, which would have the potential to carry the volcanic emissions away from the main venting area at Sulphur Springs.

When compared with the WHO 10-minute AQG of 500 μg/m^3, the average monthly SO_2 concentrations measured by the passive diffusion tubes for Group 1 sites were observed to be exposed to concentrations of SO_2 that are above the guideline during the dry season months of April to June (Fig. 4a). Of Group 1 sites, average monthly SO_2 concentrations at BHS exceeded the WHO 10-min AQG by the greatest amount, while concentrations at MVP exceeded it by the smallest amount for the dry season (Table 3). Average monthly SO_2 concentrations measured at Group 1 sites for the rainy season months of July to November were within the WHO 10-min AQG, with the exception of July for CWP and August for BHS (Table 3).

Average monthly SO_2 concentrations measured at Group 2 sites were below the WHO 10-minute AQG of 500 μg/m^3 over the entire monitoring period, with no significant seasonal variation being apparent (Fig. 4a & b). The average monthly SO_2 concentrations measured for Group 3 sites, also did not exceed the WHO 10-min AQG of 500 μg/m^3 at any time during the entire monitoring period (Fig. 4a & b).

5.3. ToxiRAE monitor readings

Ambient SO_2 concentrations recorded using a ToxiRAE monitor for the MVP site only is presented in Table 4. At the MVP, the monitoring records of the ToxiRAE indicated, that for the periods sampled, the NIOSH guideline for a STEL of 5 ppm SO_2 and the TWA of 2 ppm SO_2 over an 8 hour period were not exceeded. Hence, the health risk to workers was within acceptable limits for the measured periods at this site.

Table 3
Average monthly SO_2 concentrations for all sites monitored for the period April to December 2014.

	Site ID	GPS location		Altitude (m)	Average monthly SO_2 concentrations (μg/m^3)								
		Northing	Westing		April	May	June	July	August	September	October	November	December
Main Entrance Site	MES	13.840274	61.047348	233	158.58	199.69	131.12	61.46	161.23	173.60	316.39	139.13	222.27
Black Water Pool	BWP	13.839503	61.046574	242	**522.51**	**582.40**	**633.19**	430.10	436.20	379.90	492.70	256.92	**511.96**
Borehole Site	BHS	13.839110	61.046350	246	**778.50**	**943.10**	**914.50**	487.40	**560.19**	394.50	383.77	303.75	**615.80**
Main Viewing Platform	MVP	13.837346	61.045810	254	437.90	**623.10**	**523.60**	323.80	335.87	207.45	273.60	177.22	298.29
Gazebo Site	GSS	13.838050	61.045450	263	**709.20**	**634.00**	**688.30**	376.64	252.24	229.70	242.15	244.97	386.36
Clear Water Pool	CWP	13.837817	61.045456	258	**805.60**	**800.10**	**695.30**	**628.21**	462.92	348.60	317.54	317.54	317.54
Turning Point Site	TPS	13.837570	60.044600	276	85.81	84.78	77.44	84.10	112.00	87.00	56.00	103.26	99.98
Interpretation Centre	ICS	13.836430	61.046540	288	15.14	21.11	13.14	37.80	28.94	16.48	42.23	6.65	28.26
Soufriere Comprehensive Secondary School	SCSS	13.836430	61.048080	55	1.25	0.80	158.90	32.68	0.00	1.30	1.60	2.76	1.81
Castries Control Site	CCS	13.998680	60.994550	176	0.00	1.00	153.45	22.25	172.51	158.58	0.00	0.00	0.50

Values over the 10-minute AQG (500 μg/m^3) highlighted in bold.

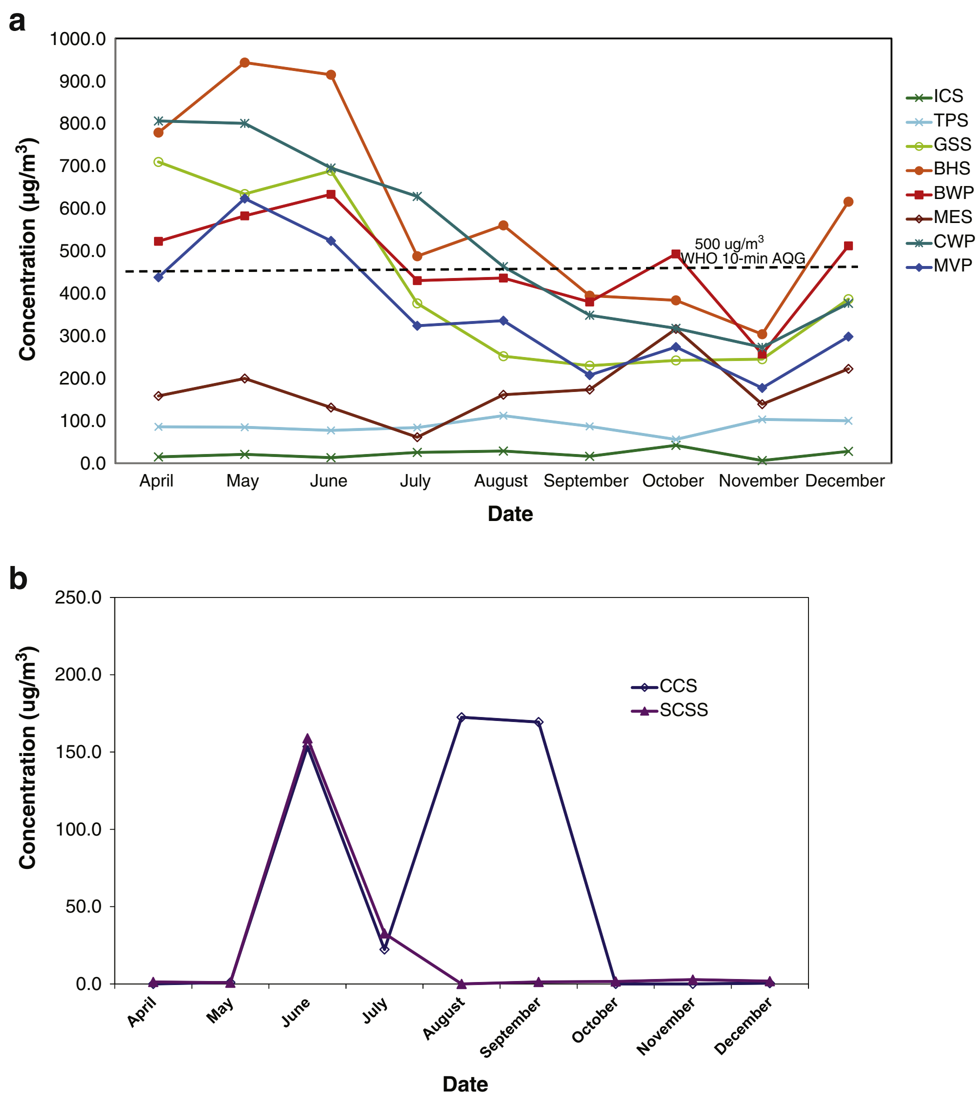

Fig. 2. (a) Average monthly atmospheric SO_2 concentrations measured at Group 1 sites; and (b) Average monthly atmospheric SO_2 concentrations measured at Group 2 and 3 sites in Saint Lucia, using passive diffusion tubes during the period April–December 2014. The WHO 10-min air quality guideline is indicated by dashed lines.

6. Discussion

6.1. Passive diffusion samplers

The use of passive diffusion tubes to measure ambient gas concentrations in volcanic environments, as well as to provide valuable information on atmospheric dispersion of volcanic and fumarolic gases has been clearly recognised (Delmelle et al., 2002; Aiuppa et al., 2007; Bhugwant et al., 2009). At SSP there is a strong relationship seen between higher average SO_2 concentrations and proximity to the main venting areas of the volcano-hydrothermal field (Fig. 3a). Sites closest to the main vents record the highest average SO_2 concentrations in the range of ~177–943 μg/m^3 throughout the entire monitoring period. The rapid decrease of ambient SO_2 concentrations away from the main vents was demonstrated by Group 2 sites which recorded lower average SO_2 concentrations in the range of ~0–200 μg/m^3. Factors contributing to this relationship include altitude and local topography of the area, as well as the influence of the plume dispersion. The main venting area of SSP is situated in a depression that is roughly delineated by the Sulphur Springs road passing through the Park (Fig. 1). This favours the accumulation of fumarolic gases more easily within the depression, and contributes to higher ambient SO_2 concentrations being recorded by sites closest to the depression (altitude of 242–254 m for Group 1 sites; Table 2), and lower concentrations at sites that were at a higher altitude (276–288 m for Group 2 sites except MES; Table 1).

Additionally, the strong influence of the topography on local atmospheric circulation facilitated the transport of fumarolic gases to the sites further away from the main venting area thereby influencing the SO_2 concentrations to which they are exposed. Concentrations of ambient SO_2 at Group 2 sites (i.e. low values at ICS and TPS and high values up to BWP and sometimes to MES) could be explained by a local prevailing southern wind, within the generally N–S trending valley in which Sulphur Springs is situated. The generally lower SO_2 concentrations observed for Group 2 sites are also consistent with gradual dilution of the plume with distance from the main venting area because of air entrainment and scavenging of SO_2 by surface deposition (Delmelle et al., 2002; Murrell et al., 2014).

Seasonal variability of ambient SO_2 concentrations was observed for Group 1 sites as depicted in Fig. 3, with higher average concentrations being recorded in the dry season and lower concentrations in the rainy season. This variability may be primarily explained by the process of wet deposition (Davies, 1967; Walcek and Pruppacher, 1984). Rainout processes facilitate removal of SO_2 in the ambient environment via falling rain. Rainout processes include interception of particles by falling raindrops and diffusional uptake of SO_2 (HSDB, 2002). The rate of SO_2 removal by wet deposition processes, combined with the rate of SO_2

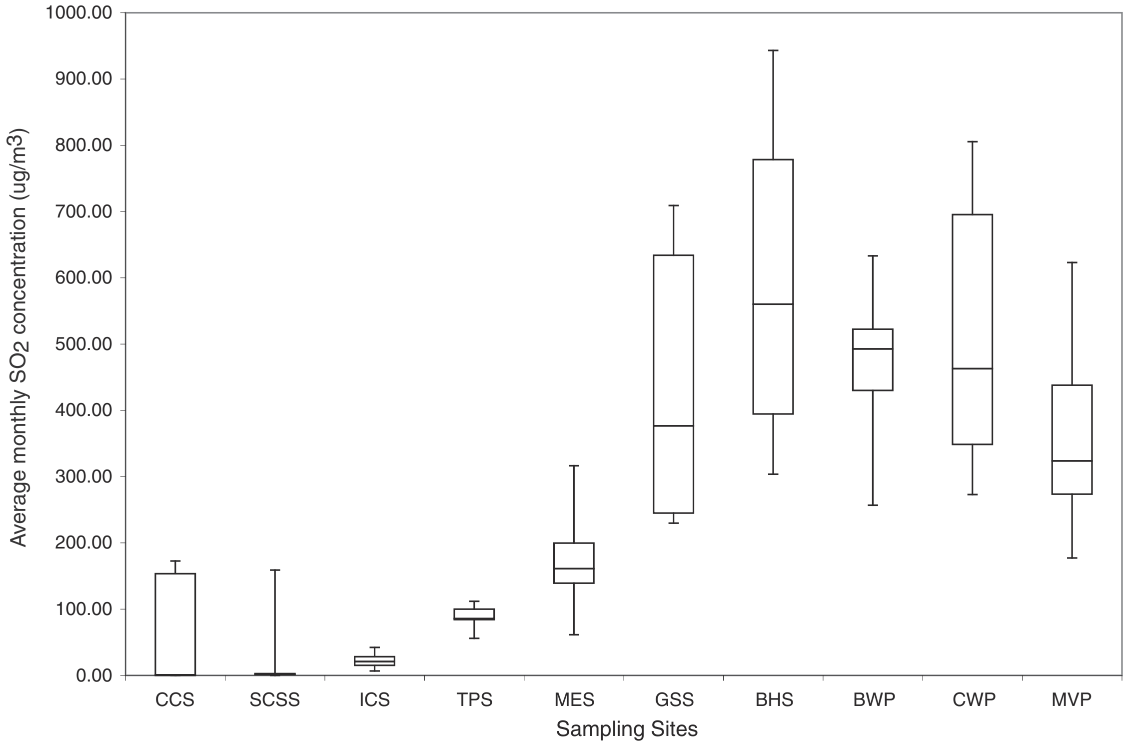

Fig. 3. Box and whisker plots showing the range in monthly SO_2 concentration, measured at each site in Saint Lucia, with passive diffusion tubes for the period April–December 2014. Boxes show the range of data between the 25th and 75th percentiles, whiskers indicate the full range of the data. The median is shown by a central bar.

emissions determines the residence time of SO_2 in the atmosphere. HSDB (2002) gives residence times ranging from 1 to 5 days, which is within the 4 week measuring period of the diffusion tubes. Evidence to support the removal of ambient SO_2 through rainout processes at SSP can be observed by the changes in average SO_2 concentration at Group 1 sites with changes in average rainfall amounts (Fig. 2 and Table 2).

Additional factors possibly contributing to the observed seasonal relationship in ambient SO_2 concentrations at Group 1 sites include seasonal variability of the amount of water available in the hydrothermal system, as well as changes in the amount of natural irradiation from season to season. During the rainy season greater availability of water in the hydrothermal system would allow for increased absorption of SO_2 i.e. gas scrubbing (Symonds et al., 2001), with less gas being released into the ambient environment. Inversely, during the dry season less water in the hydrothermal system allows for decreased interaction with the acidic gases and drier pathways for the escape of SO_2 into the surrounding atmosphere. Photochemical reactions involving the chemical oxidation of H_2S to SO_2 are more highly favourable with increased irradiation (Pham et al., 1995; D'Alessandro et al., 2009). If the availability of sunlight is used as a proxy for irradiation then this reaction may also contribute to increased SO_2 concentrations in the ambient environment at sites closest to the hydrothermal field in the dry season months of March to June, where average hours of sunshine (Table 2) was greater (8.5–10 h) as compared to the rainy season months of July to November with less average hours of sunshine (7.8–8.9 h).

The larger concentration range and higher average SO_2 concentrations observed at MES in comparison to the other Group 2 sites was primarily attributed to contributions of SO_2 by vehicular emissions, as MES is located in the car park area of SSP. The gradual dilution of the plume outwards from the main venting area at SSP, as evidenced by the significantly lower concentrations and lack of seasonal variation in ambient SO_2 at the distal Group 2 sites throughout the monitoring period, suggests that SO_2 concentrations measured at Group 3 site SCSS in the town of Soufrière are not markedly impacted by emissions from Sulphur Springs. Anthropogenic sources may have contributed to the spike in SO_2 concentration measured in June at SCSS, as no corresponding spikes were observed for Groups 1 and 2 at SSP. It may therefore be inferred that SO_2 concentrations measured at Group 3 site CCS in the town of Castries, are mainly influenced by anthropogenic contributions from sources within the town itself as it lies in the north of the island completely removed from the hydrothermal system.

6.2. Human health implications

The concentrations obtained using the passive diffusion samplers represent the integrated concentration of the gas being measured over a specific exposure period, hence short-term variability cannot be measured with this method. However, values obtained from their use can be used to identify areas with elevated atmospheric levels of SO_2 that are potentially hazardous to human health, particularly as a guide for the residents and visitors to Sulphur Springs.

In this study, measurement of ambient SO_2 concentrations at SSP indicate that there are several areas in the Park where, on numerous occasions, concentrations exceeded levels that could be life threatening to sensitive persons i.e. SO_2 at 0.25–0.5 ppm (~650–1300 μg/m^3) (Utell and Frampton, 1998). Furthermore, these areas include those utilised by visitors of SSP year round. Average monthly SO_2 concentrations, measured using the passive samplers, during the dry season months (April to June) exceeded the WHO 10-min AQG of 500 μg/m^3 at Group 1 sites MVP, CWP, BWP, and GSS, which are routinely incorporated in tour visits at SSP. These measurements are indicative that SO_2 concentrations, which are potentially dangerous to even healthy people, can be reached at SSP particularly during the dry season months or in drier periods throughout the entire year. While visitors tend to move from site to site within the Park and would normally spend ~15 min per site, there are areas such as MVP, CWP, and BWP where they may stay for half hour or more using recreational pools and sightseeing. This warrants concern as the likelihood of an adverse response to elevated SO_2 concentrations, particularly for sensitive individuals, is increased at these sites.

Furthermore, in between tours staff at SSP regularly congregate in these areas for extended periods, which can exceed 1 h, thereby increasing their risk associated with potential exposure to unsafe concentrations of SO_2 as well as health problems attributed to chronic exposure. The average SO_2 concentrations measured with the passive diffusion tubes for the rainy season months, at Group 1 sites that are frequented by

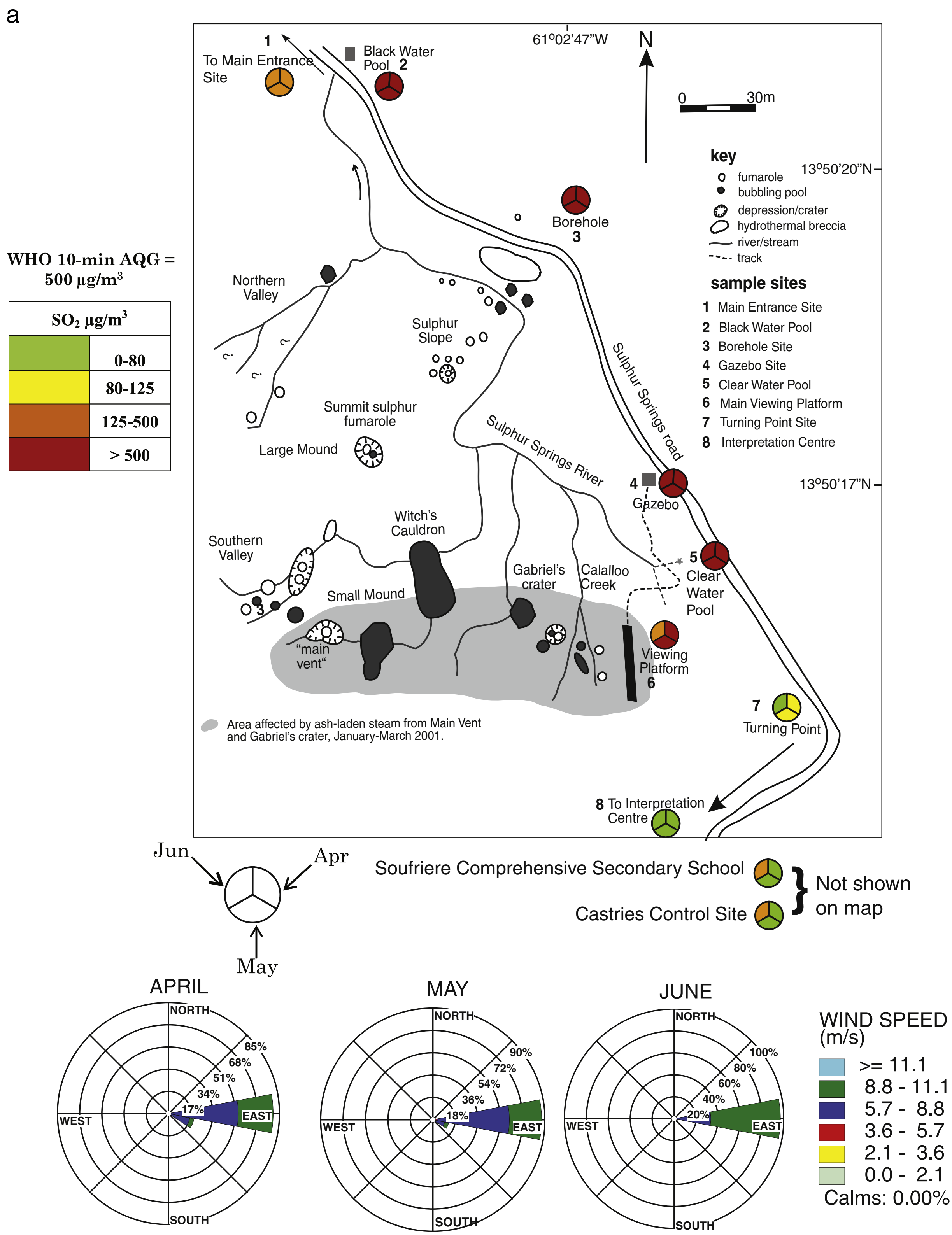

Fig. 4. (a) Map of Sulphur Springs showing the location of sampling sites where ambient SO_2 was measured with passive diffusion tubes for exposure periods of ~4 weeks during the period April–June 2014. The symbol for each site is subdivided into three sectors, each referring to a different month. The colour of the sector indicates the average monthly atmospheric SO_2 concentration. (b) Map of Sulphur Springs showing the location of sampling sites where ambient SO_2 was measured with passive diffusion tubes for exposure periods of ~4 weeks during the period July–December 2014. The symbol for each site is subdivided into six sectors, each referring to a different month. The colour of the sector indicates the average monthly atmospheric SO_2 concentration. Wind-rose diagrams showing the frequencies of different wind directions for the respective survey periods are at the bottom of the diagrams.

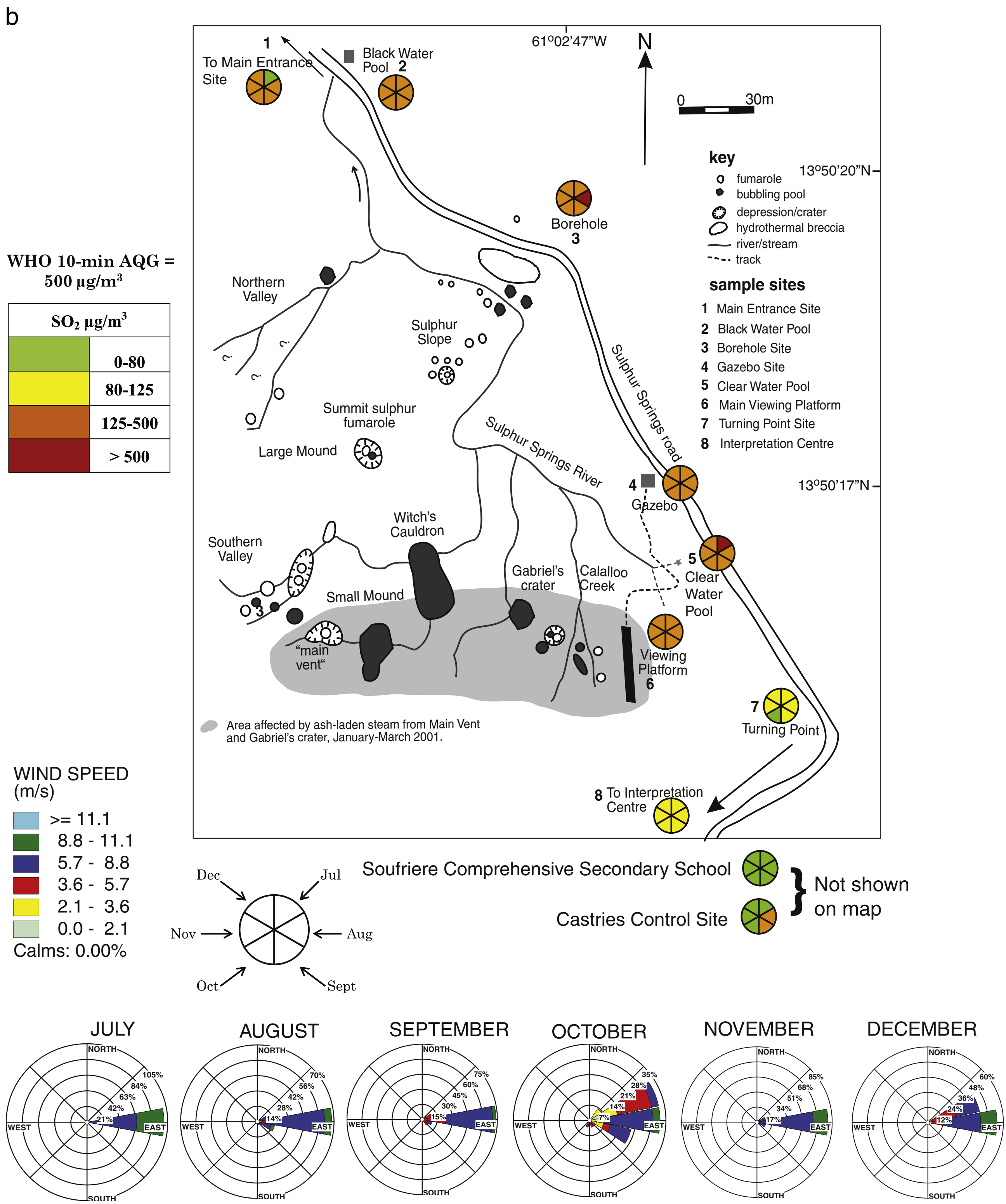

Fig. 4 (*continued*).

tourists, were within the WHO 10-min AQG. While this indicates that overall the air quality during these months was within acceptable limits at these sites, it must be considered that this method cannot resolve temporal variations of exposure. Therefore, periodic spikes in SO_2 concentrations, which may be hazardous to public health, may be interspersed with lower concentrations, and are masked by these lower monthly averages.

The monthly average SO_2 concentrations at Groups 2 and 3 sites did not exceed the WHO 10-minute AQG of 500 μg/m^3 over the entire monitoring period, indicating that the average ambient SO_2 concentrations to which residents in the area near Sulphur Springs are exposed, are within limits for protecting the most susceptible in the population to the effects of the gas i.e. asthma sufferers. However, this should not be

Table 4
Ambient SO_2 concentrations recorded using a ToxiRAE monitor for the MVP site only.

Sample date	STEL concentration range (ppm)	TWA concentration (ppm)	Peak concentration (ppm)	Number of records
24/03/2014	0.0–0.1	0	0.2	126
25/03/2014	0.0–0.1	0	0.4	178
25/03/2014	0.0–0.1	0	0.2	148
26/03/2014	0.0–0.1	0	0.3	87
26/03/2014	0.0	0	0.1	92
21/07/2014	0.0	0	0.1	59
22/07/2014	0.0–0.40	0	0.4	103

taken to mean that periodic spikes in SO_2 concentrations in these areas, which may affect susceptible persons, do not occur.

While the ToxiRAE SO_2 monitor provided limited continuous data from just one of the Group 1 sites in the Park (MVP), it can offer some insight for comparison of the exposure levels to the workers/guides at the Park based on the NIOSH guidelines. Neither the STEL, nor the TWA guidelines were exceeded for SO_2 indicating that from an occupational health standpoint, the overall air quality to which the guides were exposed was acceptable at this site during the monitored periods. In fact, based on SO_2 sensor itself having an accuracy of 0.3 ppm, the ambient SO_2 concentrations, at the MVP during the exposure times, were essentially below the detection limits of the sensor. It must be considered that this data is very limited, and a thorough assessment using a continuous monitor is required for all sites throughout the Park before comparisons to the NIOSH guidelines can be more adequately addressed.

It may be also be considered, that in the case of Sulphur Springs where gas emissions are from a natural system that cannot be regulated; the workers are subjected to the same level of exposure as that of the visitors, as they customarily accompany them on tour around the Park. Consequently, adopting the WHO 10-minute AQG of 500 μg/m^3 SO_2 for the workers, as is suggested for visitors, may be a possible alternative to ensure that they are also adequately protected. This is particularly relevant as the guides themselves are composed of similar individuals found in the general adult population, and are susceptible to the same health risks.

6.3. Stakeholder and public sensitisation

This study adopted the approach of actively engaging sectors of the public who would potentially be directly impacted by the information gained from the results of the air quality monitoring at Sulphur Springs. The NEMO, SRDF, staff of SSP, leaders of community groups and Secondary School officials in Soufrière, as well as other government stakeholders were invited to partake in several workshops held throughout the duration of the project. The main goal of the workshops were to actively discuss and address the concerns of the health hazards from emissions from Sulphur Springs based on the results of the study. The workshops were also used to promote public education materials, which were developed as a component of the study, to increase the awareness of communities living in, and visitors to Soufrière and Sulphur Springs respectively about the potential risks associated with exposure to unsafe levels of volcanic emissions and steps that may be taken to reduce these risks. These groups were selected based on their commitment to improving the quality of life in Soufrière; their ability to provide a number of distribution channels in support of increasing the awareness of adults and children, living in Sulphur Springs and its surroundings; as well as to tourists visiting the area. It was believed that this approach would facilitate the dissemination of the information obtained from the results of the study to a larger audience via these agents.

The education materials developed were in the form of printed posters and brochures, with the information presented in non-technical simple language, utilising graphics where possible to simplify the information. It was intended that the materials be distributed by the SRDF and NEMO to the various interest groups, as well as publicly displayed at Sulphur Springs. The workshops also facilitated the presentation of recommendations to the SRDF and NEMO to identify and implement measures for mitigation of the exposure to visitors and staff at Sulphur Springs. Recommendations were made such as putting up signs to warn visitors, particularly those with heart or respiratory problems, infants and young children, and pregnant women of the potential dangers; or placing limits on time spent in areas of the park that were found to be exposed to high levels of SO_2.

7. Conclusions

This study may be considered as a first attempt to quantify the ambient sulphur dioxide concentrations resulting from passive volcano-hydrothermal emissions at Sulphur Springs, Saint Lucia. The data obtained on ambient concentrations of SO_2 in and around SSP was used to provide information on dispersion and to report on the levels of concentration in relation to possible health risks to staff and visitors. Passive diffusion tubes were used in this application to identify areas with elevated concentrations that may be potentially dangerous to public health. The diffusion tubes, however, gave time-integrated values that do not provide information on temporal variations in SO_2 concentrations.

Measurements of average monthly ambient SO_2 with the passive samplers indicated that concentrations at sites (Group 1) in SSP most often used by staff and visitors exceeded levels (~650–1300 μg/m^3) that could be particularly hazardous to sensitive persons e.g., people with respiratory disease, asthma, or advanced age (WHO, 2006) during the dry season months. However, ambient SO_2 concentrations recorded in the rainy season were within acceptable the WHO 10-minute AQG. This indicates that seasonal fluctuations in ambient SO_2 concentrations occur at SSP and need to be continuously monitored for the protection of visitors and staff throughout the year.

The analysis of SO_2 data collected in parallel with meteorological parameters show that rainfall notably influences the spatial and temporal variability in SO_2 concentration at SSP, mainly due to scavenging and deposition (wet) processes. Other contributing factors include proximity to the fumarolic vents, altitude (local topography), prevailing wind direction and plume dispersion, and anthropogenic sources.

At the start of the study no information or signage concerning the potential health risk associated with elevated concentrations of volcanic emissions at SSP was publicly provided to visitors. Based on the results obtained in this study, brochures and posters were prepared for distribution and display at the Park to inform the public on possible gas hazards and precautionary measures that may be taken to help minimise their risk from elevated exposure. The staff of SSP, as well as other local disaster management officials, have also been educated on these issues through locally held workshops in an attempt to foster better understanding and undertaking of possible risk reduction measures at the Park. These include actions such as limiting time spent at sites closer to the main venting area, wearing protective clothing (long sleeved shirts and trousers), and moving to more well ventilated areas of the Park at any physical signs of irritation from the emissions. For brief tasks or unusual peak emissions gas masks may also be worn by the staff.

It is strongly recommended that future research efforts strive to better quantify the health risks facing staff, nearby residents, and visitors of SSP. It would also be beneficial to staff and visitors of SSP to have access to measurements from a continuous SO_2 analyser to assist with the assessment of air quality on a real-time basis; especially during working hours and the busy tourist season. Limits for warning and closing parts of the Park, as needed, could also be developed in tandem with the continuous monitoring efforts. This will help to develop evidence based tourism policy and improve emergency medical planning associated with volcanic activity in Saint Lucia.

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Appendix A. Supplementary data

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