Meteorological factors controlling soil gases and indoor CO$_2$ concentration: A permanent risk in degassing areas

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ABSTRACT

Furnas volcano is one of the three quiescent central volcanoes of São Miguel Island (Azores Archipelago, Portugal). Its present activity is marked by several degassing manifestations, including fumarolic fields, thermal and cold CO$_2$ springs and soil diffuse degassing areas. One of the most important soil diffuse degassing areas extends below Furnas village, located inside the volcano caldera. A continuous gas geochemistry programme was started at Furnas volcano in October 2001 with the installation of a permanent soil CO$_2$ efflux station that has coupled meteorological sensors to measure barometric pressure, rain, air and soil temperature, air humidity, soil water content and wind speed and direction. Spike-like oscillations are observed on the soil CO$_2$ efflux time series and are correlated with low barometric pressure and heavy rainfall periods. Stepwise multiple regression analysis, applied to the time series obtained, verified that the meteorological variables explain 43.3% of the gas efflux variations. To assess the impact of these influences in inhabited zones a monitoring test was conducted in a Furnas village dwelling placed where soil CO$_2$ concentration is higher than 25 vol.%. Indoor CO$_2$ air concentration measurements at the floor level reached values as higher as 20.8 vol.% during stormy weather periods. A similar test was performed in another degassing area, Mosteiros village, located on the flank of Sete Cidades volcano (S. Miguel Island), showing the same kind of relation between indoor CO$_2$ concentrations and barometric pressure. This work shows that meteorological conditions alone increase the gas exposure risk for populations living in degassing areas.

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1. Introduction

Volcanic gases can pose a permanent threat to population not only during eruptive unrest but also in quiescent phases of volcanoes (e.g. Blong, 1984; Williams-Jones and Rymer, 2000; Hansell and Oppenheimer, 2004). Soil diffuse degassing areas are potentially one of the main hazardous zones as the gases are continuously released and can rise below edifices without being noticed by the population. Carbon dioxide (CO$_2$) is amongst the most important diffused gases released by soil degassing (Allard et al., 1991; Baubron et al., 1991) and if present at in high concentrations can become particularly dangerous for public health, since it prevents oxygen respiration. Carbon dioxide is colourless, odourless, can silently affect population and above 15 vol.% may cause death by asphyxia (NIOSH/OSHA, 1981; Blong, 1984; Le Guern et al., 1982; Wong, 1996; Williams-Jones and Rymer, 2000). Table 1 summarizes the main effects of CO$_2$ exposure at different concentrations. In addition, since CO$_2$ is denser than air, it can accumulate hazardously in poorly ventilated or low-lying zones.

In the last decades several hundred deaths occurred in volcanic areas due to CO$_2$ release (Hansell and Oppenheimer, 2004; Weinstein and Cook, 2005; Hansell et al., 2006). The most catastrophic events were the Dieng Plateau (Indonesia) gas...
cloud emission, causing the death of at least 142 persons (Le Guern et al., 1982; Allard et al., 1989), and the gas release from Monoun (1984) (Giggenbach et al., 1991) and Nyos lakes (1986) (Barberi et al., 1989; Baxter and Kapila, 1989; Oskarsson, 1990) in Cameroon, which caused the deaths of 39 and 1700 persons respectively. Even in areas of quiescent volcanism, CO2 degassing may cause dangerous accidents to people and animals, as it is the case of Central Italy (Rogie et al., 2000; Pizzino et al., 2002; Beaubien et al., 2003; Carapezza et al., 2003; Barberì et al., 2007; Costa et al., 2008).

In the Azores archipelago the most recent casualties caused by CO2 exposure occurred in 1992, with the death of two tourists inside the Furna do Enxofre lava cave (Graciosa Island), due to air CO2 concentrations higher than 15 vol.% (Gaspar et al., 1998). Another hazardous situation took place in 1997, in Ribeira Seca village, on the northern flank of Fogo volcano (S. Miguel Island), where some families were indefinitely removed from their houses due to the high indoor CO2 concentrations (Gaspar et al., 1998; Ferreira et al., 2005). More recently, similar problems were identified in Mosteiros village (Sete Cidades volcano, S. Miguel Island) and in Praia do Almoxarife village (Faial Island).

This work aims to address the influence of meteorological variations on the indoor CO2 concentration. Several studies performed in different degassing areas have already shown that environmental variables may highly influence the gas released from soil (e.g. Klusman and Webster, 1981; Asher-Bolinder et al., 1991; Hinkle, 1991, 1994; Chiodini et al., 1998; Oskarsson et al., 1999; Diliberto et al., 2002; Granieri et al., 2003). This study is intended to understand if the meteorological variables that highly control the soil diffuse degassing processes may also influence the indoor CO2 values. Recently, some studies (Marley, 2001; Rowe et al., 2002; Denman et al., 2007) reported seasonal variations on the radioactive gas radon (222Rn), explained mainly by meteorological influences and occupancy factors. This work shows, not only seasonal variations on the gas flux but, above all, focus that lethal indoor CO2 concentrations may be reached in only a few hours due to extreme weather conditions, posing a hidden and permanent risk for populations. In this particular case, it was also observed that the soil CO2 efflux station could work as an early-warning system since the soil flux anticipates increases in the indoor CO2 concentration some hours prior to their occurrence.

### 2. Study area

The Azores Archipelago comprises nine volcanic islands (Fig. 1A), located where the Eurasian, American and African plates meet (Searle, 1980). Due to this complex tectonic setting seismic and volcanic activity are frequent in the archipelago. Since its settlement, in the 15th century, several volcanic eruptions and destructive earthquakes have been reported causing thousands of deaths and severe damages (e.g. Weston, 1964; Silveira et al., 2003). The islands of São Miguel, Terceira, Graciosa, Faial and Pico show important degassing areas, associated with the hydrothermal systems of some active volcanic centres, including fumarolic fields, thermal and cold CO2 springs and soil diffuse degassing zones.

S. Miguel Island is formed by three quiescent central volcanoes, Sete Cidades, Fogo and Furnas (Fig. 1B). Furnas is a trachytic central volcano and started to form around 100000 years BP. It comprises a summit depression 5×8 km wide formed by two nested calderas controlled by NW–SE and NE–SW faults (Guest et al., 1999). Ten intracaldera explosive

<table>
<thead>
<tr>
<th>CO2 concentration (%)</th>
<th>Exposure time</th>
<th>Effects</th>
<th>Occupational exposure limit</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.033</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5–3.0</td>
<td>Several hours</td>
<td>Difficulty in breathing</td>
<td>8 h/day in a work environment</td>
<td>Atmospheric air</td>
</tr>
<tr>
<td>3.0</td>
<td>–</td>
<td>–</td>
<td></td>
<td>PEL — permissible exposure limit</td>
</tr>
<tr>
<td>&gt;15 min</td>
<td>100% breathing acceleration</td>
<td>15 min</td>
<td>STEL — short-term exposure limit</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>–</td>
<td>300% breathing acceleration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>Several minutes</td>
<td>Unconsciousness. Quick recovery when the person is moved to a ventilated environment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;15.0</td>
<td>–</td>
<td>Unconsciousness and death.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – Toxicology of carbon dioxide (based on NIOSH/OSHA, 1981; Le Guern et al., 1982; Wong, 1996; Williams-Jones and Rymer, 2000)
Trachytic eruptions occurred in this volcano in the last 5000 years, two of which happened in historical times (1439–43; 1630) (Queiroz et al., 1995; Cole et al., 1995). At present, volcanic activity is marked by four main fumarolic fields, three of them located inside the volcano caldera: (1) Furnas Lake fumarolic field; (2) Furnas Village fumarolic field and (3) Ribeira dos Tambores fumarolic field. On the south flank of the volcano it can be found Ribeira Quente fumarolic field with several gas emanations occurring along Ribeira Quente stream. In Furnas village several hot springs and CO₂ cold springs are also present. Fumarole outlet temperatures are close to the boiling point of water (95–100 °C). The main components of the fumarolic discharges are water vapour (H₂O) followed by carbon dioxide (CO₂), hydrogen sulphide (H₂S), hydrogen (H₂), nitrogen (N₂), oxygen (O₂), methane (CH₄) and argon (Ar) (Table 2)(Ferreira and Oskarsson, 1999; Ferreira et al., 2005). CO₂ is the main gas released by soil diffuse degassing at Furnas. Recent work (Silva, 2006) measured values for the radioactive gas radon (²²₂Rn) in

Fig. 1 – (A) Location map of the Azores archipelago and (B) S. Miguel Island digital elevation model. Legend: (a) Sete Cidades volcano, (b) Fogo volcano and (c) Furnas volcano. The red square represents the area under study.

<table>
<thead>
<tr>
<th>Table 2 – Chemical composition of the main fumarolic fields, in molar %, from the work of Ferreira and Oskarsson (1999)⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
</tr>
<tr>
<td>Caldeira Grande LG920128</td>
</tr>
<tr>
<td>Lagoa das Furnas LG920128</td>
</tr>
<tr>
<td>Ribeira dos Tambores FU91RT03</td>
</tr>
</tbody>
</table>

Soil diffuse degassing

<table>
<thead>
<tr>
<th>Soil gas</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil CO₂ concentration (vol.%)⁸</td>
<td>0.0</td>
<td>5.2</td>
<td>94.6</td>
<td>1197</td>
</tr>
<tr>
<td>Soil temperature (°C)⁸</td>
<td>11.5</td>
<td>19.8</td>
<td>74.8</td>
<td>1197</td>
</tr>
<tr>
<td>Soil radon concentration (Bq m⁻³)⁹</td>
<td>45.9</td>
<td>6702.0</td>
<td>11,0808.0</td>
<td>175</td>
</tr>
</tbody>
</table>

the main soil diffuse degassing area in Furnas caldera and was found to be mostly associated to CO\textsubscript{2} anomalous areas.

Furnas village is located within the caldera of Furnas volcano and, according to the last Portugal census of population and housing (Census, 2001), has 1541 inhabitants living in 895 dwellings. About 22% of the buildings have raised wooden floors (Pomonis et al., 1999), which consist of old traditional construction that creates a ventilated space mostly to reduce the moisture of the wood floor. By its characteristics, this construction technique also prevents or retards the gas migration into the houses.

The mean annual precipitation in Furnas caldera, based on 65 climatological years, is 1992 mm according to Marques et al. (2007). The same authors refer that the monthly rainfall distribution exhibits seasonal pattern, with significant differences between the “rainy season” that extends between October and March, and the “dry season” with a minimum rainfall in July.

3. Previous works

Baubron et al. (1994) performed an initial soil CO\textsubscript{2} concentration map (scale 1/2000) of the inhabited area of Furnas village showing that it was built over a significant soil diffuse degassing area. A new survey, using the same methodology, was performed ten years later by Sousa (2003) covering a more extended area (Fig. 2). The data obtained in those works show soil CO\textsubscript{2} concentration and soil temperature values higher than 90 vol.% and 70 °C, respectively (Table 2). In the case of Furnas village, the soil CO\textsubscript{2} degassing anomaly looks to have remained remarkably stable between the two surveys. These studies are important for seismo-volcanic monitoring as, in future, alterations in the anomaly shape may mean significant changes in the deep system. Baxter et al. (1999) based on the work of Baubron et al. (1994) estimated that about one third of the houses at Furnas village were located in areas with high CO\textsubscript{2} degassing (>1.5 vol.% in the soil). According to the same authors, it was not possible to associate loss of human lives to high indoor CO\textsubscript{2} concentration in the Furnas area. Nevertheless, cases of dizziness in high CO\textsubscript{2} concentration areas in Furnas volcano have been described through time and can be read in historical accounts from the 16th century (Frutuoso, 1522–1591).

During our field work, some people reported breathing acceleration and asphyxia symptoms, occasionally, inside their homes. In addition, deaths of little animals (chickens, birds, cats and mice) in some non-ventilated spaces were also reported. Some persons also mentioned the empirical association between the gas increases inside houses and extreme weather conditions.

4. Methodology and results

4.1. Soil CO\textsubscript{2} efflux permanent station

In the scope of the Azores seismo-volcanic monitoring programme a soil CO\textsubscript{2} efflux permanent station (GFUR1) was...
installed at Furnas volcano in October 2001, next to the Furnas
gas field (Fig. 2). This station performs measure-
ments by the “time 0, depth 0” accumulation chamber method
(Chiodini et al., 1998) and the soil CO2 efflux value represents
the gas concentration increase inside a chamber during a
certain interval of time, which was programmed to be 130 s
for GFUR1 station. The CO2 efflux unit is g m⁻² d⁻¹. The
accumulation chamber and the station datalogger unit are
covered with a shelter. The automatic station (manufactured
by WestSystems, Italy) performs measurements on an hourly
basis and has coupled meteorological sensors. Namely it
acquires information about barometric pressure, air tempera-
ture, air relative humidity, wind speed and direction, rainfall,
soil water content and soil temperature.

The station has a local memory able to store up to 2048
measurements, however every hour the data are transmitted
to the Centre of Volcanology and Geological Risks Assessment
in the University of the Azores via GSM telemetry system.
Sensor types, as well as the descriptive statistics of the main
studied variables, are shown in Table 3.

Time series acquired by the different sensors are plotted
in Fig. 3 and show that some meteorological variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
<th>Std. Dev.</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFUR1 soil CO2 efflux (g m⁻² d⁻¹)</td>
<td>26.0</td>
<td>245.9</td>
<td>1313.3</td>
<td>87.0</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 barometric pressure (hPa)</td>
<td>964.7</td>
<td>998.9</td>
<td>1012.3</td>
<td>7.1</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 rainfall (mm h⁻¹)</td>
<td>0.0</td>
<td>0.4</td>
<td>22.8</td>
<td>1.6</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 air relative humidity (%)</td>
<td>52.4</td>
<td>89.8</td>
<td>98.2</td>
<td>11.2</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 air temperature (°C)</td>
<td>1.2</td>
<td>11.3</td>
<td>20.6</td>
<td>3.3</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 wind speed (m s⁻¹)</td>
<td>0.0</td>
<td>0.6</td>
<td>8.0</td>
<td>1.0</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 soil temperature (°C)</td>
<td>12.0</td>
<td>13.8</td>
<td>15.6</td>
<td>0.7</td>
<td>1173</td>
</tr>
<tr>
<td>GFUR1 soil water content (%)</td>
<td>22.3</td>
<td>27.5</td>
<td>48.7</td>
<td>2.7</td>
<td>1173</td>
</tr>
<tr>
<td>Indoor CO2 concentration (vol.%)</td>
<td>0.2</td>
<td>4.7</td>
<td>20.8</td>
<td>3.1</td>
<td>1011</td>
</tr>
<tr>
<td>GA barometric pressure (hPa)</td>
<td>948.0</td>
<td>983.5</td>
<td>995.0</td>
<td>7.4</td>
<td>1011</td>
</tr>
</tbody>
</table>

Fig. 3 – Variation of the soil CO2 efflux and the barometric pressure (A)/rainfall (B) at GFUR1 between 3rd February and 24th March 2003.
influence the gas flux oscillations. From all the monitored variables, barometric pressure showed an evident negative correlation with the gas flux (Fig. 3A). Significant spike-like increases in the gas flux can also be observed concomitantly to intense rainfall periods (Fig. 3B). Long-term changes are observed in the soil CO₂ efflux time series registered at GFUR1 during 4 years (Fig. 4). Excluding the first year of data acquisition, the data show that soil CO₂ efflux values are higher during winter months than in summer months. These tendencies may be explained by the lower barometric pressure values and the intense rainfall events that are more frequent in winter periods and may cause a global increase on the gas flux. In order to understand and quantify the environmental influences on the gas flux, stepwise multiple regression analysis (Draper and Smith, 1981) was applied to the data series obtained at the GFUR1 station, from 3rd February to 24th March 2003, the period used to perform this monitoring test. Soil CO₂ efflux was used as dependent variable and the monitored meteorological variables were tested as the independent variables. All the monitored variables were tested, being included in the regression model only the significant ones (based on the t test significance) and the variables that increase the adjusted $R^2$ more than a threshold of 1% (Draper and Smith, 1981; Freund and Wilson, 1998). This adjusted $R^2$ value is a measure of the amount of variation about the mean explained by the fitted regression equation (Draper and Smith, 1981).

The statistical analysis confirmed most of the preliminary observed relations between the monitored variables and showed that 43.3% of the soil CO₂ efflux variation (adjusted $R^2$ value, Table 4) can be explained by the influence of the environmental monitored variables. Rainfall, barometric pressure and soil temperature are the variables with statistical meaning to explain the gas oscillations ($P < 0.01$). Coefficient $\beta$ expresses the influence of each independent variable on the CO₂ efflux (Draper and Smith, 1981). According to the coefficient $\beta$ sign, barometric pressure has a linear negative relationship with the gas flux. By contrast, rainfall and soil temperature have a positive correlation with the gas flux. Rainfall gives rise to different effects (Table 4) on the gas flux depending on the rain amount and, for this reason, the same physical variable is split into two data series, one for values lower than 8 mm h$^{-1}$ and other one for values above that threshold. It is possible to observe that both data sets show a positive correlation with the gas flux. Rainfall gives rise to different effects (Table 4) on the gas flux depending on the rain amount and, for this reason, the same physical variable is split into two data series, one for values lower than 8 mm h$^{-1}$ and other one for values above that threshold. It is possible to observe that both data sets show a positive correlation with the gas flux, but the coefficient $\beta$ shows different weights. In fact, the increase in the soil CO₂ efflux is more evident for high rainfall periods (>8 mm h$^{-1}$) (observe on Table 4 the coefficient $\beta$ value). Analyzing the

### Table 4 – Stepwise multiple regression analysis for data obtained at GFUR1 between 3rd February and 24th March 2003

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Coefficient $B$</th>
<th>Standard error of $B$</th>
<th>Coefficient $\beta$</th>
<th>t test</th>
<th>Signif. of t test</th>
<th>Adjusted $R^2$ increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>4283.43</td>
<td>310.70</td>
<td></td>
<td>13.79</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Rain (&lt;8 mm h$^{-1}$)</td>
<td>21.66</td>
<td>2.28</td>
<td>0.26</td>
<td>9.52</td>
<td>0.00</td>
<td>28.8</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>$-4.28$</td>
<td>0.33</td>
<td>$-0.35$</td>
<td>$-12.94$</td>
<td>0.00</td>
<td>6.9</td>
</tr>
<tr>
<td>Rain (&gt;8 mm h$^{-1}$)</td>
<td>34.78</td>
<td>2.95</td>
<td>0.31</td>
<td>11.80</td>
<td>0.000</td>
<td>6.3</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>16.33</td>
<td>3.08</td>
<td>0.14</td>
<td>5.31</td>
<td>0.000</td>
<td>1.3</td>
</tr>
<tr>
<td>Number of observations (N)</td>
<td>1173</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adjusted $R^2$ (%) = 43.3</td>
</tr>
</tbody>
</table>
adjusted $R^2$ changes, rainfall appears as the most influencing variable. By contrast, soil temperature is the one with the least relationship to gas flux.

4.2. Indoor CO$_2$ measurements

Spike-like oscillations of the gas flux may be caused by variations in meteorological factors, as demonstrated in the previous section. In order to check the impact of these meteorological influences on indoor CO$_2$ concentration, an experiment was performed during February and March 2003 in a selected house at Furnas village (Fig. 2), during a period with no significant seismic activity. This house is built over an area without a significant thermal anomaly and with soil CO$_2$ concentration ranging from 25 to 50 vol.% (Sousa, 2003). The building has two floors with a raised wooden ground floor.

The CO$_2$ indoor values were registered with a portable infrared CO$_2$ concentration analyser equipped with a datalogger (ANAGAS$^\text{TM}$ CD 95 model from Geotechnical Instruments, United Kingdom) that also registers the barometric pressure values. CO$_2$ concentrations are measured in vol.% from 0 to 100, with 0.5% precision. The equipment was installed at the ground floor, in a bedroom, and the sampling point was set at the floor level.

Data was acquired every hour from 3rd February to 24th March 2003 and was programmed to be contemporaneous with data acquired at GFUR1, located about 0.5 km far from the selected house (Fig. 2).

The CO$_2$ concentration in the bedroom ranged between 0.2 and 20.8 vol.% with an average of 4.7 vol.% (Table 3). The same time, the soil CO$_2$ efflux values at GFUR1 changed from 26.0 g m$^{-2}$ d$^{-1}$ to 1313.3 g m$^{-2}$ d$^{-1}$. During the monitored time,
95% of the indoor CO\(_2\) values were above 0.5 vol.%, which is the Permissible Exposure Limit (PEL) for an 8 h working environment period defined by the National Institute of Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA) in the United States (NIOSH/OSHA, 1981) and the Commission of the European Communities (1991, 2006). The minimum value registered was 0.2 vol.%, six times higher than the average atmospheric air CO\(_2\) concentration (Table 1). The maximum value obtained, 20.8 vol.%, is about forty times higher than the PEL.

Fig. 5 shows that the higher CO\(_2\) concentration values are negatively correlated with the barometric pressure and occur some hours after heavy rainfall periods. The influence of the other monitored variables on indoor gas concentration was not possible to establish.

Comparing the indoor CO\(_2\) concentration and the soil CO\(_2\) efflux values at GFUR1 (Fig. 6) it is possible to observe that increases in the soil gas flux values foresee for some hours (from 5 to 10 h) the indoor CO\(_2\) concentration increases.

Recently, a similar test was performed in a house located on Mosteiros village on the Sete Cidades volcano flank, in the western part of S. Miguel Island. The infrared detector was installed in the 1st floor of a house located in an area where soil CO\(_2\) concentration values range between 5 and 10 vol.%. Data were acquired on an hourly basis between 1st April and 31st December 2006. The indoor CO\(_2\) concentration ranged between 0 and 17.4 vol.%, with an average value of 0.6 vol.%. It was also possible to observe significant increases on the indoor CO\(_2\) concentration, which are coincident with decreases in the barometric pressure (Fig. 7).

The most influent meteorological variables on the gas flux oscillations at the monitoring sites at Furnas volcano are the barometric pressure and the rainfall. The inverse correlation between barometric pressure and soil CO\(_2\) efflux has already been observed in other volcanic systems (e.g. Chiodini et al., 1998; Rogie et al., 2001; Granieri et al., 2003) and can be explained by the upward migration of gases from deeper layers due to a decrease in the barometric pressure and a driven back of the gas into the ground during barometric pressure increases, the so-called barometric pumping effect (Auer et al., 1996; Martinez and Nilson, 1999; Neeper, 2001). Rainfall influence is split into two intervals positively correlated with flux, but for rainfall amounts higher than 8 mm h\(^{-1}\), the positive relationship is more significant. This positive effect on the gas flux may be partially related with a covering effect of these stations that allows the gas to escape through the dry area. During heavy rainfall periods, the soil around the CO\(_2\) efflux station gets completely saturated filling all the pores with water and obstructing gas release to the surface; thus the accumulation chamber site remains dryer for a longer time favouring the gas flux below it. All the gas filling in the voids in the surrounding area is conveyed in this place, causing the observed positive spike-like anomalies that are more significant for values higher than 8 mm h\(^{-1}\). The same phenomenon seems to occur in a broader scale in the zone located below the dwellings, since the indoor CO\(_2\) concentration increase is observed some hours after rainfall episodes. This positive correlation between the soil CO\(_2\) efflux and the rainfall is not observed in all the permanent stations installed at S. Miguel Island (Viveiros et al., in press). Despite the covering effect of the stations, topographic effects and drainage area may also play an important role. Soil temperature influence only appears when barometric pressure and rainfall are not important. This positive correlation may be potentially explained by the drying of the superficial soil layers causing slight increases in permeability and consequently in the soil CO\(_2\) efflux.

5. Discussion and conclusions

Stepwise multiple regression analysis seems appropriate to understand the relations between the different monitored variables. Based on this statistical analysis, it is also possible to remove the meteorological influences from the gas flux.
During extreme meteorological conditions, characterized by low barometric pressure and intense rainfall, the indoor CO2 concentration at the Furnas house reaches the highest values. Despite the similar behaviour showed by soil CO2 efflux and indoor CO2 concentrations, the sharp increases do not occur simultaneously with indoor CO2 increase being delayed for some hours (from 5 to 10 h) in relation to the soil CO2 efflux increase. This delay time response may be due to the presence of the vented space that exists below the house allowing the aeration and dilution of the gas prior to its ingress into the house.

The described indoor gas behaviour shows that the gas hazard increases during extreme weather conditions. In addition, the ventilation of the houses is highly reduced during these periods, once the house occupants tend to close doors and windows.

Some spike-like changes detected by previous works (Baxter et al., 1999) in dwellings at Furnas village were attributed to non-registered microseismicity, however considering rain data from that time, those increases can be explained by extreme meteorological conditions.

Several works (e.g. King, 1993; Salazar et al., 2002; Beaubien et al., 2003) related gas changes in degassing areas with seismic activity however, this work shows that increases in the gas flux and concentration inside dwellings can occur solely induced by meteorological changes. During the period under analysis the seismo-volcanic activity both at Furnas and Sete Cidades volcanoes was quite low, so it is considered that the meteorological influences were responsible for the observed gas flux and concentrations oscillations.

The lethal CO2 concentration values obtained during the monitoring test indicate that, even though currently volcanism in the Azores is quiescent, the population is at permanent risk from exposure to CO2. In addition, it is necessary to consider that the sharp gas increases occur in a few hours and when it happens during the night the risk is even greater. The lethal values obtained in the monitoring tests at Mosteiros and Furnas villages were registered on houses located in low and middle risk zones, respectively (according to the Baubron et al., 1994 classification) and not in the highest CO2 soil concentration anomalous areas. Furthermore, the raised wooden floor in the Furnas village case should supposedly diminish the house’s vulnerability to the volcanic gases, but it seems that only retards the gas increase in the house. This points to even higher indoor CO2 values at other more vulnerable houses placed in higher CO2 soil concentration areas. Future works should extend these monitoring tests to other houses at Furnas village, in different anomalous degassing areas, in order to choose the permanent station to be used as an early-warning system to hazardous situations.

In this work the gas studied was the CO2, one of the most important in volcanic regions, however, there are other gases released diffusely by the soil, including 222Rn and H2S that can also be influenced by the same meteorological factors as CO2 with all the consequences for the public health that will imply. The H2S is other gas released in geothermal areas and concentrations higher than 700 ppm may be lethal (Beaubien et al., 2003; Durand and Scott, 2005). No detailed H2S mapping is available for Furnas village; nevertheless some occasional measurements were done along the main soil diffuse degassing area and was only detected near the fumaroles. Further studies need to be carried out to understand the hazard associated with this particular gas.

The obtained results and the experience from other cases in the Azores Archipelago, confirm that even areas with no visible gas manifestations show lethal CO2 concentrations, leading to an ideal situation that should be to forbid building in certain degassing areas. Soil diffuse degassing anomaly maps should constitute a fundamental tool used by the land-use planners in order to select the proper areas to build.

Unfortunately there are already several populated areas built over degassing areas and, even if we consider that the most advisable scenario should be removing the population from these dangerous areas, we know that these drastic resolutions are unrealistic to apply. For this reason, at least several mitigation measures should be taken into consideration and some construction techniques should be introduced. Not allowing the construction of basements or cellars, installation of natural ventilation systems and the use of an impermeable membrane are some of the possible rules that should be legislated for buildings located in degassing areas, similarly to the earthquake-resistant construction that already exists in active seismic areas.

Even though the house under study has a raised wooden floor that could be considered as a preventive mitigation measure there is still gas ingress into it. It seems that the system may retard the entry of the gas into the house but it will not solve the problem. As a cautionary note, efforts were made in Rotorua, New Zealand, to mitigate gas flux into houses, but the preventive measures failed after some years (Durand and Scott, 2005). So, we must insist that the referred mitigation measures may delay the problem, but do not solve it completely and that the best solution should be not allowing to build in degassing areas.

This work emphasizes the existing hidden permanent risk that should be taken into account for public health risk assessment purposes in all degassing areas, since significant gas flux increases may occur even in quiescent periods of volcanic activity, due only to meteorological factors.

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