Journal of Volcanology and Geothermal Research 177 (2008) 883–893

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Environmental influences on soil CO_2 degassing at Furnas and Fogo volcanoes (São Miguel Island, Azores archipelago)

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ARTICLE INFO

Article history:
Received 13 February 2008
Accepted 3 July 2008
Available online 19 July 2008

Keywords:
volcanic gases
soil diffuse degassing
monitoring
soil CO2 flux
Azores archipelago

ABSTRACT

Since October 2001, four soil CO_2 flux stations were installed in the island of São Miguel (Azores archipelago), at Fogo and Furnas quiescent central volcanoes. These stations perform measurements by the accumulation chamber method and, as the gas flux may be influenced by external variables, the stations are equipped with several meteorological sensors. Multivariate regression analysis applied to the large datasets obtained allowed observing that the meteorological variables may influence the soil CO_2 flux oscillations from 18% to 50.5% at the different monitoring sites. Additionally, it was observed that meteorological variables (mainly soil water content, barometric pressure, wind speed and rainfall) play a different role in the control of the gas flux, depending on the selected monitoring site and may cause significant short-term (spike-like) fluctuations. These divergences may be potentially explained by the porosity and hydraulic conductivity of the soils, topographic effects, drainage area and different exposure of the monitoring sites to the weather conditions. Seasonal effects are responsible for long-term oscillations on the gas flux.

Before a reliable application of soil CO_2 flux to seismic and/or volcanic monitoring, it is important to recognize those environmental influences on the gas flux. In addition, understanding the external meteorological influences on the gas flux may be important for the public health risk assessment, since meteorological parameters may cause also significant indoor CO_2 increases. In a house at Furnas Village (in Furnas volcano caldera), the values detected reached percentages as high as 20.8% due to significant decreases in the barometric pressure.

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1. Introduction

Soil diffuse degassing studies have been applied on several volcanic areas over the last two decades showing that, even during periods of quiescence, volcanoes may release a high amount of gas to the atmosphere (e.g. Allard et al., 1991; Chiodini et al., 1996, 1998; Werner et al., 2000; Bergfeld et al., 2001; Brombach et al., 2001; Cardellini et al., 2003; Notsu et al., 2005).

Even if only recently soil gas continuous measurements started to be applied in volcanic systems, some geochemical changes already emerged (1) before eruptive periods (Carapezza et al., 2004), (2) associated to high magnitude earthquakes (Salazar et al., 2002), or (3) related to seismic swarms and fluids intrusion episodes without culminating in volcanic eruptions (Granieri et al., 2003; Salazar et al., 2004). However, several works noticed the influence of environmental and meteorological variables on volcanic gas emissions (e.g. Klusman and Webster, 1981; Asher-Bolinder et al., 1991; Hinkle, 1991, 1994; Mcgee and Gerlach, 1998; Rogie et al., 2001; Diliberto et al., 2002; Granieri et al., 2003; Hernández et al., 2004; Lewicki et al., 2007). The influence of these external parameters on the gas flux must be understood; otherwise short-term and/or long-term variations of data may be misinterpreted as due to deep-sited changes on the system.

Continuous soil CO_2 flux programme started on the Azores archipelago on October 2001. Several datasets were obtained, being possible to observe spike-like oscillations on the gas flux even during these years of quiescent activity. This paper shows the long monitoring data obtained at four permanent gas flux stations installed at São Miguel Island and intends to establish the baseline behaviour for the soil CO_2 flux at each monitoring site. Multivariate regression analysis is applied in order to understand the nature of the temporal variations, mainly the short-term oscillations observed on the gas flux datasets. It also emphasises the different influence of the meteorological parameters on the gas flux, as it also hypothesizes several explanations for the different responses of the gas flux at each monitored point.

2. Geological setting and monitoring sites characterization

The Azores archipelago comprises nine volcanic islands, located where the Eurasian, American and African lithospheric plates meet (Searle, 1980). On account of this complex tectonic setting, seismic and volcanic activities are frequent in the archipelago. Since the settlement

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doi:10.1016/j.jvolgeores.2008.07.005

of the islands, in the 15th century, several destructive earthquakes and more than thirty volcanic eruptions have been reported, causing thousands of deaths and severe damages (e. g. Weston, 1964; Silveira et al., 2003). Present-day volcanic activity in the Azores archipelago is marked by several hydrothermal manifestations consisting of active fumarolic fields, thermal and CO_2 cold springs and soil diffuse degassing areas.

Furnas and Fogo volcanoes are two of the three quiescent polygenetic volcanoes of São Miguel Island (Fig. 1), where it is possible to observe all the referred hydrothermal manifestations. Furnas volcano started to be formed at about 100,000 BP and it has an impressive summit 5×8 km depression formed by two nested calderas controlled by NW-SE and NE-SW faults (Guest et al., 1999). Since the settlement of the island, two trachytic intracaldera eruptions occurred, one in 1439–1443 (Queiroz et al., 1995) and the other in 1630 (Cole et al., 1995). This last eruption was responsible for the death of at least 190 persons.

Furnas volcano is considered to have the most important degassing areas of the archipelago (Ferreira and Oskarsson, 1999; Cruz et al., 1999; Ferreira et al., 2005) with the presence of four main fumarolic fields. From those, three are located inside Furnas caldera, known as Furnas Village, Furnas Lake and Ribeira dos Tambores and its designation is correlated with their geographical location. In the south flank of the volcano there is Ribeira Quente village with several steam emissions, not only near the houses, but also along the path of Ribeira Quente river. Since the early nineties, soil CO_2 concentration surveys have been carried out at Furnas volcano caldera (Baubron et al., 1994; Baxter et al., 1999; Sousa, 2003). The results showed that one of the major soil diffuse degassing areas extends below Furnas village, with some houses located in areas where the risk of asphyxia is high (Baxter et al., 1999). Symptoms related to CO_2 exposure and the deaths of animals are sometimes described by the population. Historical accounts from the 16th century already reported dizziness of people in some depressed zones at Furnas volcano (Frutuoso, 1522–1591).

A preliminary survey with a soil CO_2 flux portable station was performed at Furnas caldera in order to select the best site for setting up a permanent station.

According to the manufacturer, the optimal soil CO_2 flux values for installing these stations are in the range from 100 to 15,000 g m^{-2} d^{-1}. Following these criteria, the first soil CO_2 flux permanent station (named GFUR1) (Fig. 1) was installed in October 2001 near Furnas Village

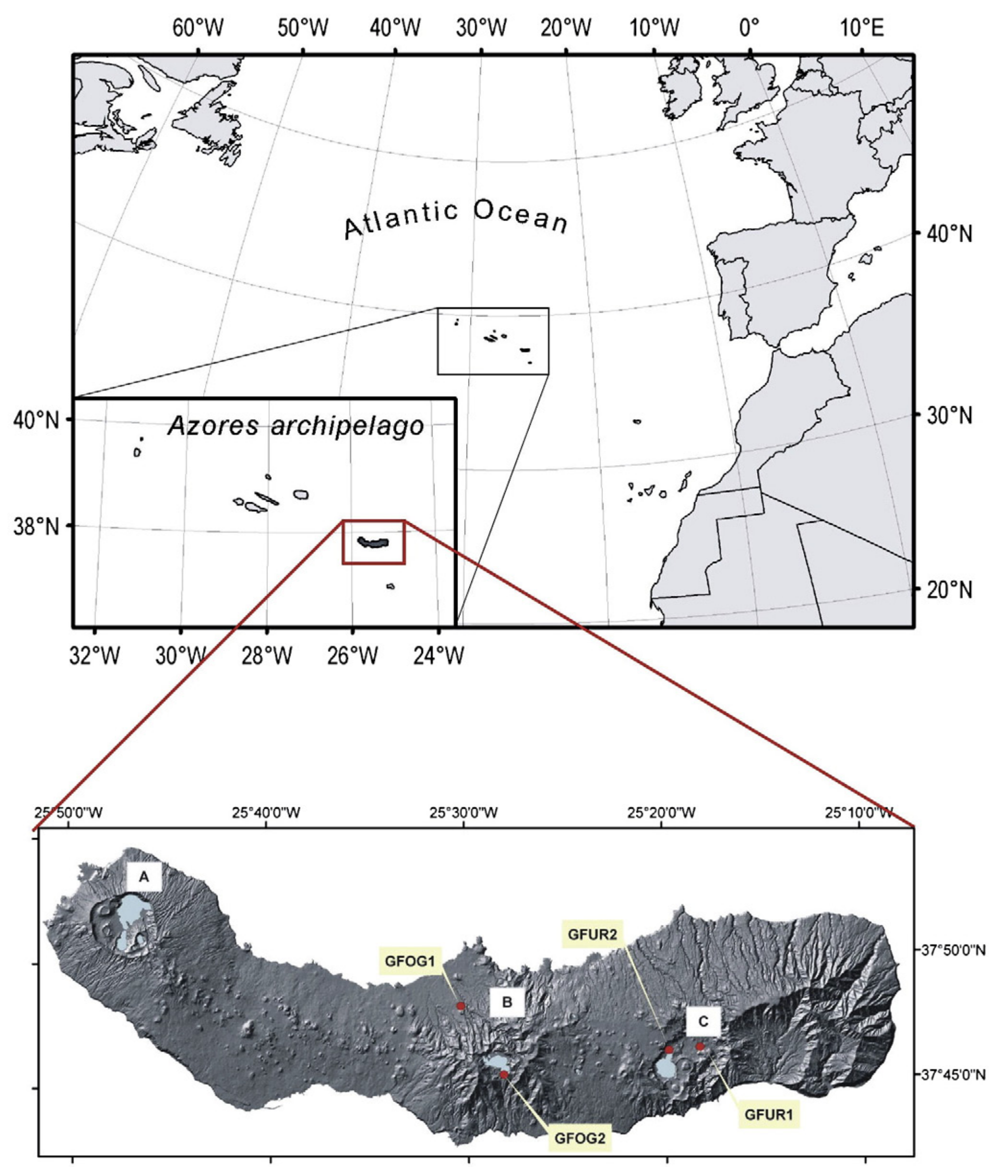

Fig. 1. Azores archipelago setting highlighting São Miguel Island. (a) Digital Elevation Model of the São Miguel Island with the location of the automatic monitoring gas flux stations. The caps lock letters represent the active polygenetic volcanoes: A — Sete Cidades volcano; B — Fogo volcano; C — Furnas volcano.

fumarolic field in an area with soil CO_2 flux values around 260 g m^{-2} d^{-1}. The non-existence of temperature anomaly in the selected site was also considered, as it could cause some condensation along the sampling channel and lead to erroneous measurements on the gas flux. A second soil CO_2 flux station (named GFUR2) was installed in the vicinity of Furnas Lake fumarolic field (Fig. 1) in October 2004, where soil CO_2 flux values of around 350 g m^{-2} d^{-1} were measured.

Fogo volcano is located in the central part of São Miguel and its formation began around 200,000 years ago (Muecke et al., 1974). Five trachytic explosive eruptions took place in the area over the last 5000 years, with the last one occurring in 1563, and it was characterized by a Plinian intracaldera eruption that was followed, 4 days later, by a basaltic flank eruption (Booth et al., 1978; Wallenstein, 1999).

The main degassing areas at Fogo volcano are located in its northern flank associated to the NW-SE fault system that defines the so-called Ribeira Grande graben. The degassing manifestations comprise three main fumarolic fields: Caldeira Velha, Caldeiras da Ribeira Grande and Pico Vermelho. GFOG1 (Fig. 1) was the first soil CO_2 flux permanent station installed in this volcanic system, in February 2002, at the Pico Vermelho geothermal area where it was measured an average value of 600 g m^{-2} d^{-1}. The work performed by Marcos et al. (2003) defined the Pico Vermelho soil diffuse degassing anomaly with CO_2 concentrations in the soil as being as high as 96.6% vol., thus confirming the importance of the chosen site for monitoring purposes. GFOG1 station was removed from its site in May 2006 due to a new geothermal power plant that was built in Pico Vermelho geothermal area. Consequently, it was necessary to wait for the conclusion of the construction works and let the environment conditions around the station stabilize again, otherwise the works would affect the gas flux values obtained. Since 2003, several low magnitude seismic swarms have occurred at Fogo volcano and at the east side of Congro volcanic System, reaching the maximum peak in its activity during 2005, when thousands of low magnitude earthquakes were registered. Due to this increase in the seismic activity, a second soil CO_2 flux station (named GFOG2) was installed inside the caldera of Fogo, in May 2005 (Fig. 1), even though the soil CO_2 flux values in the area were very low (around 8 g m^{-2} d^{-1}). The strongest seismic event (magnitude, M_L=4.3) occurred on 2005, September 21st, and it represented the most important seismic activity that affected the island during the period under analysis.

Soil type can have an indirect effect on gas concentrations in the soil (Asher-Bolinder et al., 1991; Hinkle, 1994; Hernández et al., 2004). Furnas and Fogo volcanoes soils are developed over quite similar pyroclastic and ash volcanic deposits due to the similarities between both volcanic systems. In general, soil textures are mostly fine sand with some gravel (Paulo Amaral, personal communication, 2008) and the organic matter content is lower than 12%.

3. Methodology

3.1. Equipment

At the present time, four automatic stations installed to measure the soil CO_2 flux (manufactured by WestSystems, Italy) are running on São Miguel Island, two in Furnas and two in Fogo volcanoes. The stations perform measurements based on the "time 0, depth 0" accumulation chamber method (Parkinson, 1981; Chiodini et al., 1998). Every hour, a chamber is lowered on the ground and the gas is pumped into a CO_2 detector (Dräger Polytron IR Transmitter Sensor). The soil CO_2 flux value is calculated by the CO_2 concentration increase inside the chamber during a precise period of time. These measurements have a reproducibility of 10% for the CO_2 range between 10 and 20,000 g m^{-2} d^{-1} (Chiodini et al., 1998). The applied methodology allows measuring the gas flux independently from the transport regime and the soil proprieties (Chiodini et al., 1998; Granieri et al., 2003; Carapezza and Granieri, 2004). The automatic stations simultaneously acquire information related to the barometric pressure, air temperature, air relative humidity, wind speed and direction, rainfall, soil water content and soil temperature.

Each station is powered with a battery recharged by a solar panel and has a local memory able to store up to 2048 measurements. Every hour the acquired data is transmitted to the Centre of Volcanology and Geological Risk Assessment in the University of the Azores via GSM (in the case of Furnas volcano stations) or via freewave (Fogo volcano stations) telemetry systems.

3.2. Statistical analyses

The data obtained from the permanent stations were statistically processed to establish relationships between meteorological parameters and soil CO_2 flux and to remove the signal attributed to the meteorological processes from the raw CO_2 flux time series. Stepwise multivariate regression analysis (Draper and Smith, 1981; Freund and Wilson, 1998) was applied to the different time series, with the soil CO_2 flux being considered the dependent variable and the monitored meteorological parameters the independent variables. All the monitored variables were tested and only the significant ones, according to the *t* test, and the variables that increase the *adjusted* R^2 more than a threshold of 1% (Draper and Smith, 1981), were included in the regression models. 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 *t* test rejects the null hypothesis for each of the independent variables that have no explanatory power at 0.01 levels of significance. Some variables do not show a straight linear correlation with the gas flux, but instead show relationships described with curved lines. These models are called polynomial and correspond to a linear function of powers of one or more independent variables and they can be applied as a linear regression (Freund and Wilson, 1998). In the present study, some models are second order polynomial evidencing a quadratic shape (Freund and Wilson, 1998).

Parametric methods, as the regression analysis, usually require that populations follow normal distributions (Draper and Smith, 1981). As a general rule, geochemical and environmental data do not strictly follow normal or log-normal distributions (Reimann and Filzmoser, 1999). In this study case, since there are a high number of observations involved in the regression, the data approach the normality as it is expected by the central limits theorem. For this reason, it was decided to use the untransformed data for the application of multivariate regression analysis. When one applies multivariate regression analysis, it is necessary to consider that some additional unmonitored variables may also influence the gas flux oscillations and some of the independent monitored variables may evidence dependence and multicollinearity (existence of high correlation among the independent variables) (Draper and Smith, 1981; Freund and Wilson, 1998). If the later is true, it may be more difficult to interpret the regression results and understand which variable shows stronger correlation with the gas flux. For this reason, the *variance inflation factor* (VIF) (Freund and Wilson, 1998; Adnan et al., 2006) is a common method used to verify the existence of multicollinearity and it measures how much the variance of the estimated regression coefficients is increased compared to when the independent variable are uncorrelated. A typical cutoff value for VIF is 10 and any VIF value larger than this implies stronger relationships among the independent variables (Freund and Wilson, 1998).

4. Data analysis and results

Descriptive statistics and the correlation coefficients of the acquired data by the permanent stations are shown in Table 1. GFOG2 station is located in the area characterized by the lowest soil CO_2 flux degassing, while GFOG1 registers the highest average values of soil CO_2 flux. None of the permanent stations is located in an area with thermal anomaly. GFOG2 station was installed inside the caldera of Fogo volcano during

Table 1
Descriptive statistics of the data acquired in the permanent stations installed in São Miguel Island

Variables	Average	S.D.	Max.	Min.	Number of data	Pearson correlation coefficient between dependent–independent variable	Period under analyze
GFUR1							
Soil CO_2 flux (g m^{-2} d^{-1})	266.6	98.3	2485.6	2.2	37,175	1.00	Mar-02 to May-06
CO_2 in the air (ppm)	477.7	258.3	3752.8	38.2	37,152	0.17	Mar-02 to May-06
Soil temperature (°C)	17.5	2.7	23.9	12.0	36,966	−0.22	Mar-02 to May-06
Soil water content (%)	22.5	6.2	62.1	6.2	35,954	0.11	Mar-02 to May-06
Barometric pressure (hPa)	999.7	7.6	1019.8	958.4	37,272	−0.40	Mar-02 to May-06
Rain (mm)	0.3	1.4	41.8	0.0	34,877	0.35	Mar-02 to May-06
Air relative humidity (%)	92.5	9.8	98.2	31.6	37,272	0.21	Mar-02 to May-06
Air temperature (°C)	15.4	4.1	29.9	1.2	37,272	−0.16	Mar-02 to May-06
Wind speed (m s^{-1})	0.4	0.7	10.5	0.0	37,086	0.13	Mar-02 to May-06
GFUR2							
Soil CO_2 flux (g m^{-2} d^{-1})	386.4	115.7	857.7	7.4	12,387	1.00	Jan-05 to May-06
CO_2 in the air (ppm)	278.6	114.2	1665.9	93.9	12,387	0.47	Jan-05 to May-06
Soil temperature (°C)	19.5	2.3	24.7	15.2	12,388	0.10	Jan-05 to May-06
Soil water content (%)	22.0	4.3	42.7	11.2	12,388	−0.29	Jan-05 to May-06
Barometric pressure (hPa)	987.5	8.4	1006.8	955.2	12,388	0.34	Jan-05 to May-06
Rain (mm)	0.3	1.3	25.6	0.0	12,388	−0.22	Jan-05 to May-06
Air relative humidity (%)	84.3	9.1	98.5	43.8	12,372	−0.07	Jan-05 to May-06
Air temperature (°C)	15.6	3.5	29.0	6.5	12,372	−0.26	Jan-05 to May-06
Wind speed (m s^{-1})	1.0	1.0	10.8	0.0	12,372	−0.39	Jan-05 to May-06
GFOG1							
Soil CO_2 flux (g m^{-2} d^{-1})	600.0	221.9	4605.4	17.1	36,289	1.00	Mar-02 to Apr-06
CO_2 in the air (ppm)	286.2	93.2	1274.4	4.5	36,289	0.17	Mar-02 to Apr-06
Soil temperature (°C)	19.6	3.1	25.9	13.6	36,522	0.07	Mar-02 to Apr-06
Soil water content (%)	35.4	3.3	54.7	26.7	36,527	0.00	Mar-02 to Apr-06
Barometric pressure (hPa)	1002.8	7.7	1023.3	960.0	36,527	0.02	Mar-02 to Apr-06
Rain (mm)	0.2	1.1	38.2	0.0	36,526	0.13	Mar-02 to Apr-06
Air relative humidity (%)	87.4	11.1	98.4	28.6	36,434	0.07	Mar-02 to Apr-06
Air temperature (°C)	15.3	3.7	28.1	4.5	36,286	0.04	Mar-02 to Apr-06
Wind speed (m s^{-1})	1.8	1.7	12.4	0.0	35,921	−0.09	Mar-02 to Apr-06
GFOG2							
Soil CO_2 flux (g m^{-2} d^{-1})	8.0	4.2	55.0	0.0	6352	1.00	Jul-05 to May-06
CO_2 in the air (ppm)	180.8	27.5	265.1	124.9	2611	0.66	Jul-05 to May-06
Soil temperature (°C)	15.1	2.7	19.8	11.1	8619	0.53	Jul-05 to May-06
Soil water content (%)	15.4	4.8	44.9	8.6	8619	−0.52	Jul-05 to May-06
Barometric pressure (hPa)	944.3	7.3	960.1	918.2	8620	0.20	Jul-05 to May-06
Rain (mm)	0.2	0.9	26.2	0.0	8617	0.04	Jul-05 to May-06
Air relative humidity (%)	89.4	8.0	99.1	35.5	8614	−0.05	Jul-05 to May-06
Air temperature (°C)	13.8	3.5	27.5	6.1	8615	0.39	Jul-05 to May-06
Wind speed (m s^{-1})	2.6	2.3	16.5	0.0	8616	−0.14	Jul-05 to May-06

the 2005 Fogo seismic crisis with the main purpose of detecting any increase in the gas flux and/or in the soil temperature that could show signs of unrest in the volcanic system. As the soil CO_2 flux values at GFOG2 station are very low and the recording period is shorter when compared with the other monitoring flux stations, it was decided not to apply any statistical model to these data.

The best period to check meteorological influences on the gas flux and define the soil CO_2 flux baseline is during "quiet" periods of seismic and/or volcanic activity. In the case of data from the GFUR1 and GFOG1 stations, the time selected to build the regression model was the period between August 2003 and August 2004. During this year, no significant seismic activity affected Furnas volcano, however some seismic swarms were already affecting Fogo volcano area. For this reason, the number of seismic events was also included in the regression model at GFOG1 in order to test its influence. The dataset acquired between January and December 2005 was selected to define the regression model at GFUR2, as it was the first complete year of data recording without gaps in the meteorological parameters.

Table 2
Multivariate regression analysis for data acquired at GFUR1 between August 2003 and August 2004

	Coefficient *B*	Standard error of *B*	Coefficient β	*t* test	Signif[a] of *t* test	Adjusted R^2 increase	VIF
Independent variable							
Intercept	5509.84	140.91		39.10	0.00		
Soil water content	3.65	0.29	0.13	12.76	0.00	0.259	1.64
Barometric pressure	−5.05	0.14	−0.30	−36.75	0.00	0.102	1.41
Soil temperature	−16.49	0.35	−0.43	−46.74	0.00	0.082	1.16
Rain	28.50	1.09	0.37	26.10	0.00	0.056	3.39
$(Rain)^2$	−0.62	0.06	−0.14	−10.20	0.00	0.006	3.20
Adjusted R^2						0.505	
Dependent variable: soil CO_2 flux							
Number of observations	8461						

[a] Statistical significance of the correlation between each individual variable and the soil CO_2 flux.

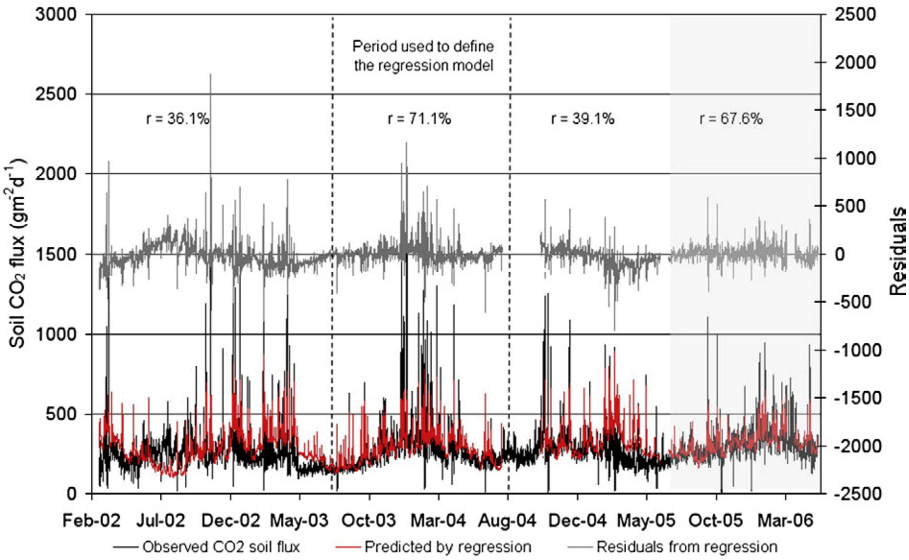

Fig. 2. Observed, *predicted* and *residuals* soil CO_2 flux relative to GFUR1 station. The grey shadow evidences the period for which different coefficient β were defined, due to the replacement of the soil water content sensor.

4.1. GFUR1 station

A stepwise multivariate regression model was applied to the acquired data at GFUR1 between August 2003 and August 2004. Soil water content, barometric pressure, soil temperature and rainfall are the statistically meaningful variables that can explain the observed gas flux fluctuations. Judging from the *adjusted* R^2 value, these monitored variables account for 50.5% of the soil CO_2 flux variation.

Coefficient β expresses the relationship (direct or inverse) between each independent variable and the dependent one, soil CO_2 flux in this case (Draper and Smith, 1981). According to the coefficient β sign, barometric pressure and soil temperature show a linear inverse correlation with the gas flux. Soil water content has a direct correlation with the gas flux. Rainfall influence is modelled as a second order polynomial variable since it has a positive correlation for gas flux until 23 mm/h, changing the correlation sign for negative above that threshold. The value for which the sign of the correlation changes is designated *stationary point* (Freund and Wilson, 1998).

Based on the *adjusted* R^2 changes (Table 2), soil water content and barometric pressure have the greatest influence on soil CO_2 flux, whereas rain has less influence. According with the VIF values, which are lower than 10, all the variables considered for the regression do not show multicollinearity.

According with the external influences proposed by the regression model, it was possible to calculate the *predicted* values for the soil CO_2 flux between March 2002 and June 2005 (Fig. 2). It is also possible to observe a shadow in the time period from July 2005 to May 2006, which is justified by a technical problem on the soil water content sensor (table with technical information is available as “Supplementary data”). Due to the replacement of this sensor, the reference values for this parameter changed and the model was adapted with slightly different coefficient β values.

Residuals are calculated through the difference between the measured soil CO_2 flux values (observed) and the *predicted* and they correspond to the values that could not be explained by the model (Draper and Smith, 1981). Thus, the *residuals* include the influence of external variables that were not monitored (e.g. earth-tides), but may also represent changes related to deeper processes in the volcanic system. For this reason, the *residuals* are soil CO_2 fluxes that have been filtered for variations associated with background meteorological processes and can be used as the baseline for monitoring purposes. Pearson correlation coefficient between the observed and the *predicted* values shows good values throughout the period used to define the regression model, however the correlation coefficients are lower on the periods previous and after the construction of the regression model. Despite these low values, it is possible to observe, from Fig. 2, that the *predicted* and the observed values have similar pattern and that the residuals do not show any trend.

4.2. GFUR2 station

The statistically meaningful monitored variables that explain the soil CO_2 flux variations at GFUR2 are wind speed, soil water content and air temperature (Table 3). These variables together explain 41.9% of the gas

Table 3
Multivariate regression analysis for data acquired at GFUR2 between January and December 2005

	Coefficient *B*	Standard error of *B*	Coefficient β	*t* test	Signif[a] of *t* test	Adjusted R^2 increase	VIF
Independent variable							
Intercept	604.48	20.14		30.02	0.00		
Wind speed	−24.21	1.11	−0.20	−21.84	0.00	0.164	1.24
(Soil water content)^2	−0.68	0.03	−1.18	−20.45	0.00	0.133	49.76
Air temperature	−16.62	0.33	−0.52	−50.76	0.00	0.111	1.55
Soil water content	19.66	1.54	0.75	12.77	0.00	0.011	52.17
Adjusted R^2						0.419	
Dependent variable: soil CO_2 flux							
Number of observations	8750						

[a] Statistical significance of the correlation between each individual variable and the soil CO_2 flux.

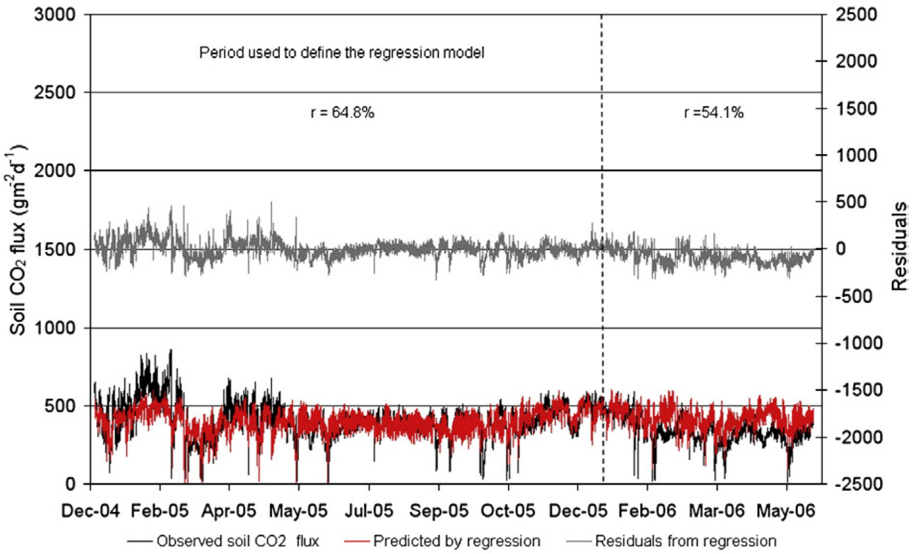

Fig. 3. Observed, *predicted* and *residuals* soil CO_2 flux relative to GFUR2 station.

flux variations (according to the *adjusted* R^2 value). Wind speed appears as the main controlling variable with a negative influence on the gas flux (coefficient $\beta=-0.2$; Table 3). This negative influence is also observed for soil water content. This last variable correlates with the soil CO_2 flux as a quadratic polynomial curve which shows a positive correlation for values lower than 14.5% and the sign of the correlation changes for higher values. Based on the regression proposed, the *predicted* and the *residual* values were calculated (Fig. 3). In this case, the Pearson correlation coefficient was quite similar for both the period used to build the regression and the following months. In fact, the *residuals* dataset shows low scattering comparing with the similar dataset obtained to GFUR1 station.

The VIF values for soil water content are higher than 10, however this multicollinearity is accepted since we are considering the same physical variable, but in a second order of influence.

4.3. GFOG1 station

The period selected to define the regression model at GFOG1 station was the same used to GFUR1, from August 2003 to August 2004. From the analysis of Table 4, it is possible to observe that the meteorological variables only explain 18.1% of the soil CO_2 flux variation. Soil temperature appears as the main controlling variable, with a negative correlation with the gas flux. Rain behaves as a second order polynomial function, with a direct relationship with the gas flux for values lower than 13 mm/h and inverse for higher values. Fig. 4 shows the *predicted* and the observed values for the period under analyze. Even during the period chosen to build the regression model, the Pearson correlation coefficient is lower than 50% (Fig. 4). It is necessary to consider that, during this period, the Fogo volcano area was affected by several seismic swarms and because of this, the hourly number of seismic events was included as a dependent variable on the regression. This variable did not show statistical significance to explain the soil CO_2 flux oscillations.

The GFOG1 station is located near a geothermal power plant that, over the last years, suffered several changes in its productivity levels. The periods of inoperability of the power plant are signed in Fig. 4, but during the periods of energy production we do not have information to include in the regression model. After May 2005, some works of soil remobilization in the area around the permanent station started, because the geothermal power plant was re-structured. It is possible to observe a negative trend on the residuals after the beginning of the works.

5. Discussion

Meteorological variables monitored in this study explain between 18% and 50.5% of the soil CO_2 flux variations at the permanent stations installed in São Miguel Island. The remaining oscillation is likely explained by the background hydrothermal variations and by the influence of other unmonitored variables. If left uncharacterized and unquantified, meteorological influences on the gas flux may be responsible for erroneous interpretations of the geochemical data, such as correlating changes in soil CO_2 flux values with the seismic and/or volcanic activity. Therefore, it is important to apply statistical analysis to the raw data in order to remove the external influences and

Table 4
Multivariate regression analysis for data acquired at GFOG1 between August 2003 and August 2004

	Coefficient *B*	Standard error of *B*	Coefficient β	*t* test	Signif[a] of *t* test	Adjusted R^2 increase	VIF
Independent variable							
Intercept	603.03	36.75		16.41	0.00		
Soil temperature	−15.01	0.73	−0.24	−20.50	0.00	0.12	1.44
Soil water content	12.25	0.75	0.19	16.36	0.00	0.031	1.46
$(Rain)^2$	−1.84	0.13	−0.24	−13.80	0.00	0.018	3.24
Rain	48.02	2.69	0.31	17.87	0.00	0.012	3.26
Adjusted R^2						0.181	
Dependent variable: soil CO_2 flux							
Number of observations (*N*)	8777						

[a]Statistical significance of the correlation between each individual variable and the soil CO_2 flux.

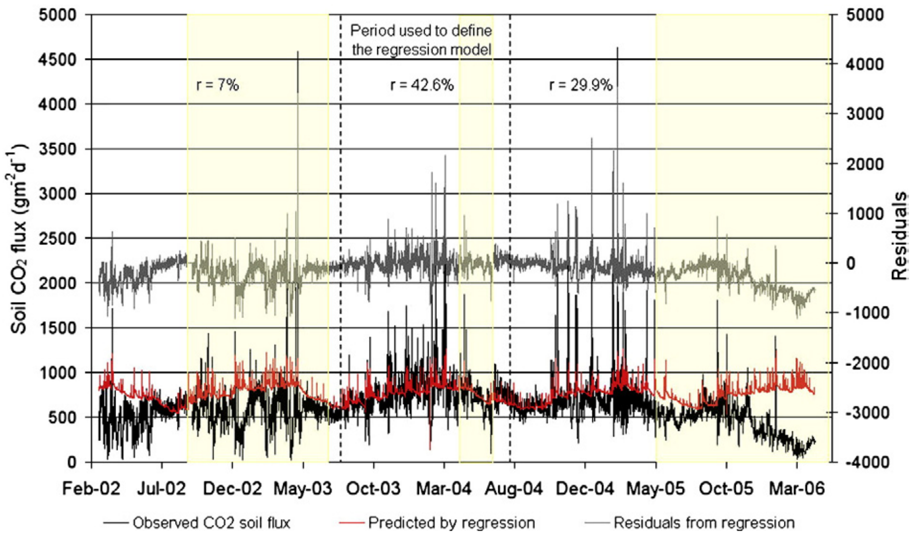

Fig. 4. Observed, *predicted* and *residuals* soil CO_2 flux relative to GFOG1 station. The yellow shadows represent the periods in which the geothermal power plant was not in production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

define the baseline behaviour for the soil CO_2 flux in each monitoring site. Multivariate regression analysis showed that barometric pressure, wind speed, rainfall, soil water content, soil and air temperature influence gas flux to different extent depending on the site.

It was used 1 year of data to build the regression models for each permanent station in order to include the seasonal effect on the gas flux behaviour.

Rainfall and/or soil water content are statistically significant for explaining the soil CO_2 flux in all the permanent stations installed. Nevertheless, the type of relation between variable independent and variable dependent is different according to the monitoring site. These meteorological variables are responsible for significant spiky variations on the gas flux (Fig. 5A, B).

Meteorological variables are not always correlated with the soil CO_2 flux in a strict linear way. This is the case of the rainfall at GFUR1 and GFOG1 stations and the soil water content at GFUR2 monitoring site, which show a second order polynomial regression with the gas flux. This means that, depending on the intensity of the rainfall, the soil CO_2 flux shows different response.

Soil water content and rainfall variables are correlated, but they do not evidence multicollinearity according the VIF parameter. At GFUR1 and GFOG1 stations these meteorological parameters behave similarly. Soil water content has a positive linear correlation with the gas flux and the rainfall has the same positive relation until a certain threshold, changing the correlation sign to negative after that. In case of GFUR1, the rainfall threshold is 23 mm/h and at GFOG1 is 13 mm/h. This positive influence during periods of rainfall, with subsequent increase in the soil water content, is potentially related with a join effect of the topography and the covering effect of the stations shelter. These two monitoring sites are located in a slightly elevated position considering the surrounding area, so rainfall drains towards the low-lying areas forming an impermeable barrier for the gas that diverts to the highest areas. The covering effect of the stations allows the gas to escape through the dry area. During rainfall periods, the soil around the station gets wet, saturating all the pores with water and obstructing the gas way out to the surface. Thus, the accumulation chamber site remains the only dry place and all the gas filling in the voids in the surrounding area is conveyed in this place, causing positive spike-like anomalies. In case of extremely heavy rainfall events, the entire soil becomes saturated and the soil CO_2 flux decreases to very low values as even at the station site. The different threshold for which the soil gets completely saturated in the referred stations is probably related with the proprieties of the soil. In fact, if the soil at GFOG1 site shows lower hydraulic conductivity and porosity than at GFUR1, less amount of rain should be also required to saturate it and that could explain the lower limit obtained for the stationary point at GFOG1. At GFUR2 station, the rain does not appear as a significant variable, however the soil water content appears as the second most influencing variable with different correlations signs. There is a positive correlation between the soil water content and the gas flux for values lower than 14.5% (Table 3), nevertheless the highest influence is evidenced by the spiky negative responses of the gas flux when the soil water content is superior to the stationary point. This faster and almost instantaneous saturation of the soil at GFUR2 station (Fig. 5B) may be, in part, related to topographic effect and drainage area. This station is located in an area with some inclination near a lake, so when there is a high rainfall the water in the soil flows preferentially to the low areas and saturates the soil under the station faster than at the monitoring sites located in higher positions.

In the case of GFUR2 station, wind speed is the variable with main influence on the gas flux. The inverse correlation observed between soil CO_2 flux and wind speed suggests that wind dilutes the soil gas, pushing some air into the upper parts of the soil during high wind speed events. Even if the soil around the flux stations is covered with grass, it seems that is not enough to prevent the wind "intrusion". This immediate gas flux response to high wind speed may be potentially increased by higher soil porosity and fracturation in the area. This could be in agreement with the referred influence of the soil water content at this monitoring site that evidences an area of higher percolation, facilitated by a more porous soil. Lewicki et al. (2007) observed a strong inverse correlation between wind speed and soil CO_2 flux at 1-day time lag at Mammoth Mountain. These authors suggested as explanation the mixing of the air with magmatic CO_2 at depth that could cause some changes in the CO_2 source up-flow to the vadose zone. It should be necessary to obtain extra spatio-temporal flux data to test if the same phenomena could explain the oscillations that we observe in this work. In spite of the influence of wind speed on gas flux at GFUR2 station, this variable does not show a significant control on soil CO_2 flux behaviour at the other station located in Furnas volcano. This can also be explained by the position of the GFUR1 monitoring site, which is near a natural barrier that protects the station from the wind.

At GFUR1, the negative influence of the barometric pressure on the gas flux appears with an explanatory power of 10% (Table 2), which is likely due to the barometric pumping effect (Auer et al., 1996; Martinez and Nilson, 1999; Neeper, 2001). This inverse correlation was also observed at flux monitoring stations in other volcanic systems, e.g., La Fossa Crater in the Vulcano Island (Chiodini et al., 1998), and Vesuvius

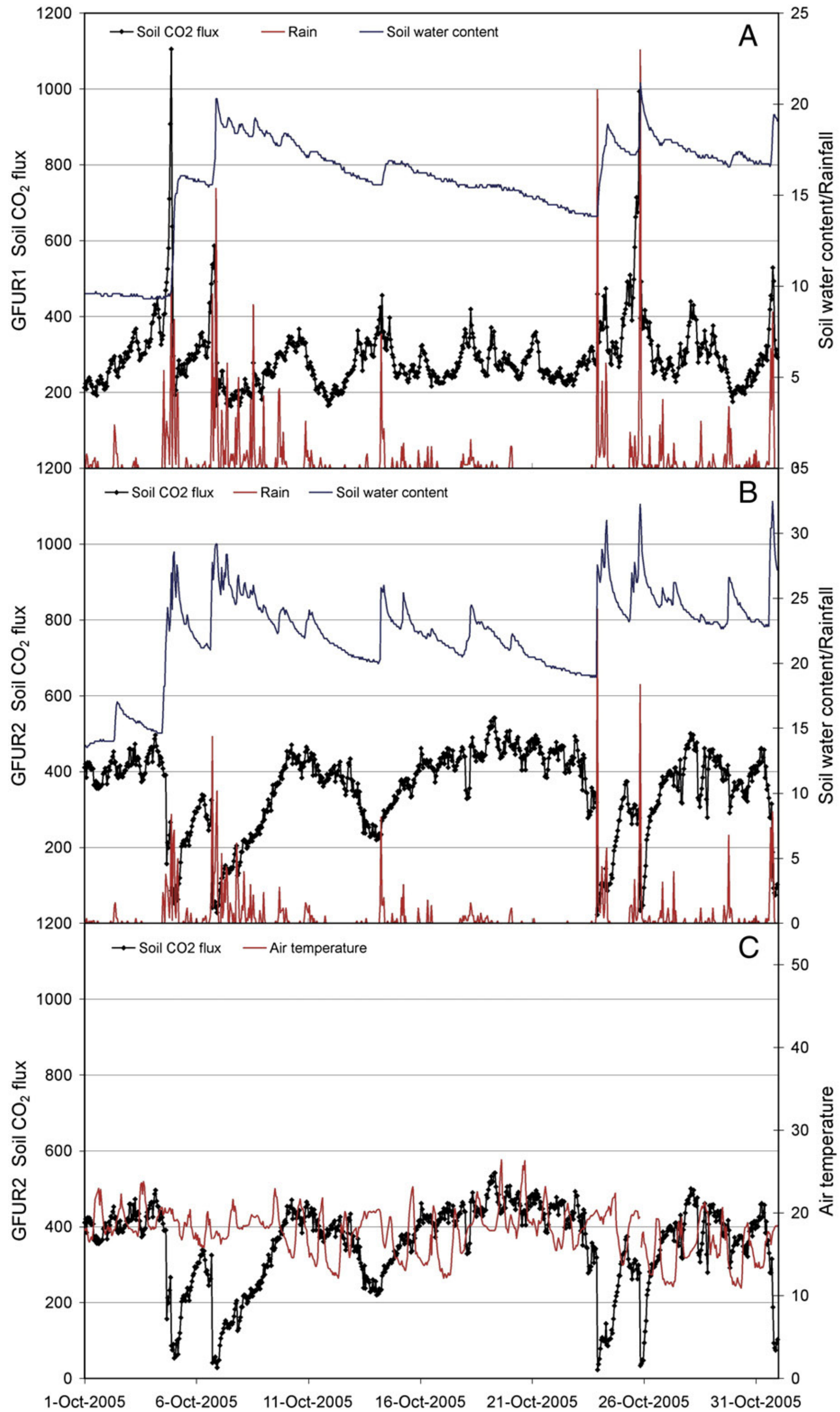

Fig. 5. Soil CO_2 flux, rainfall and soil water content variations observed at GFUR1 (A) and GFUR2 (B) during October 2005. (C) Soil CO_2 flux and air temperature variations at GFU2 during October 2005.

(Granieri et al., 2003). Rogie et al. (2001) also noticed this inverse correlation with data at diurnal and semi-diurnal time scales at Mammoth Mountain; however, they observed a positive correlation for longer time scales. The main purpose of this work is to explain spike-like oscillations and correlate data at short scale. It is possible, though, that for longer time scales the correlation between flux and the meteorological variables change due to the cross-correlation between the variables and the superimpose influence of other more influencing ones.

Soil temperature has a negative linear relation with the gas flux, both at GFUR1 and GFOG1 stations, being the most influencing variable in this last station. In fact, this inverse correlation seems to be explained by long-term seasonal effects (Fig. 6), since it is possible to observe lower soil CO_2 flux values during summer months and higher soil CO_2 flux in winter months, at least during the last 3 years of data acquisition. This is the case where a longer time scale seems to superimpose the short time scale influences.

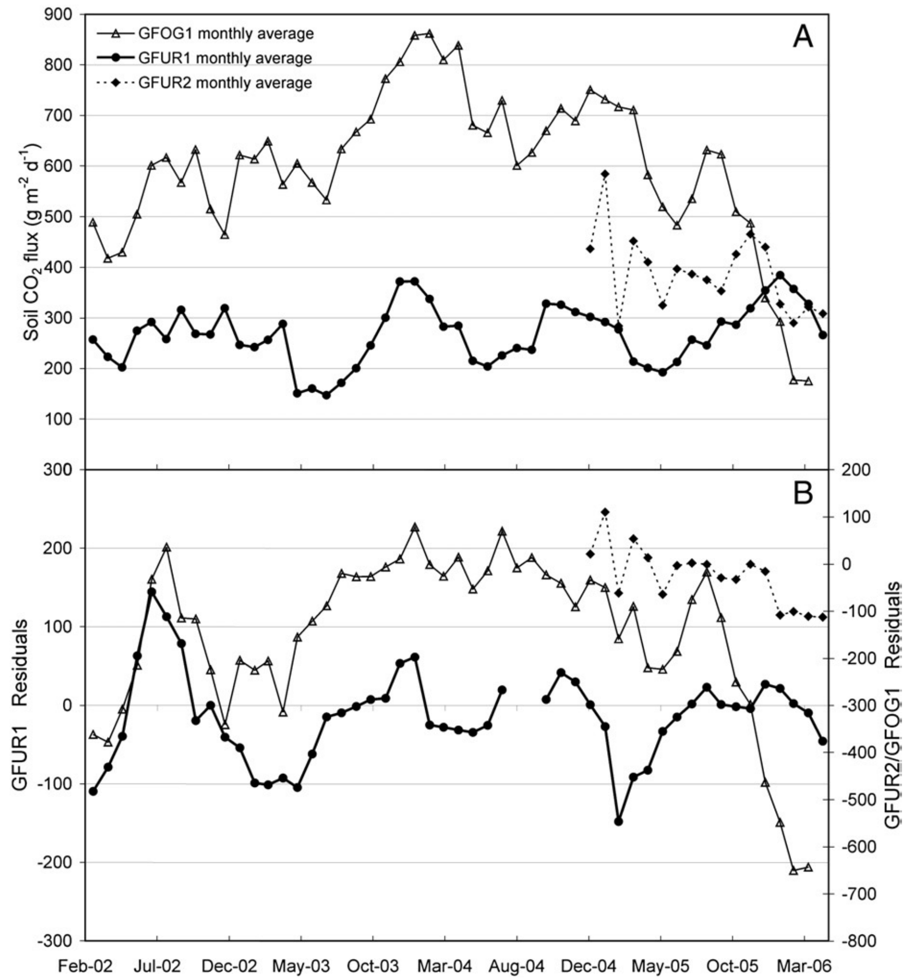

Fig. 6. Monthly average of the soil CO_2 flux observed (A) and the *residuals* (B) at the permanent stations installed in São Miguel Island.

Atmospheric tides are regular fluctuations in the atmosphere that can be primarily forced by the regular day/night cycle and insolation of the atmosphere (Chapman and Lindzen, 1970) and can have periods of 12 and 24 h. The observed linear inverse correlation between air temperature and soil CO_2 flux at GFUR2 station may be interpreted as an indirect measure of the influence of these atmospheric tides. At this station site, during periods of stable meteorological conditions, the soil CO_2 flux shows daily positive peaks during the night and negative peaks during the afternoon, which are inversely correlated to the air temperature (Fig. 5C). In this case, we can hypothesize the air temperature as an indirect measure of the insolation and consequently indicative of the atmospheric tides. These relations are possible to observe

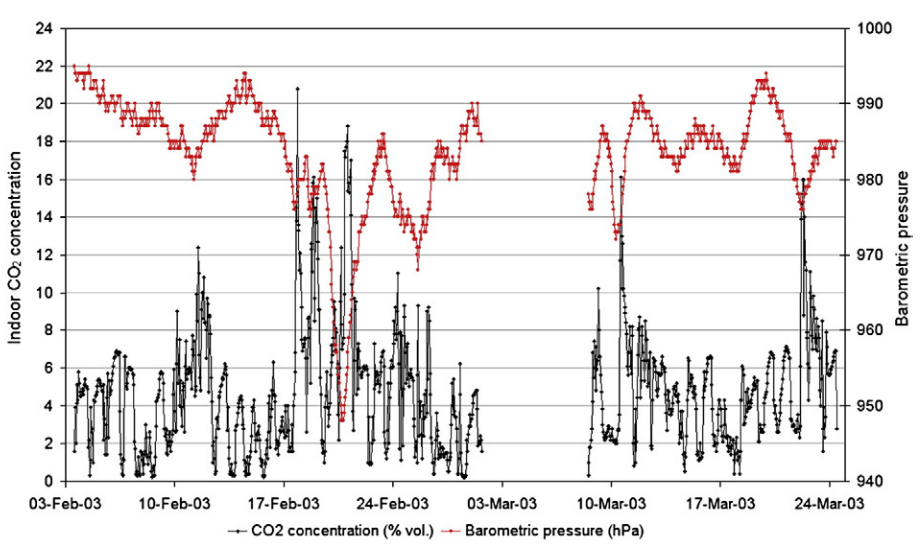

Fig. 7. Indoor CO_2 concentration and barometric pressure variations measured inside a house at Furnas Village between February and March 2003.

mainly during stable weather conditions, when the gas flux does not show spiky variations. As it was already mentioned, the soil CO_2 flux at this station does not show as many extreme values as in the other monitoring sites, which may allow to easily verify these harmonic oscillations in this station when compared to the others.

Soil CO_2 fluxes measured at the stations in São Miguel Island seem to show higher amplitudes when compared with data acquired in other volcanic systems, as it is the case of Mammoth Mountain (Rogie et al., 2001) or Solfatara (Granieri et al., 2003) volcanoes. This is probably related with the extreme meteorological conditions that affect the Azores archipelago. It was observed that the spike-like variations shown by the studied time series are mostly related with sharp variations in some of the monitored meteorological variables.

During summer time, the meteorological conditions are more stable, being possible to observe lower gas oscillations with less spike-like episodes during those periods (Figs. 3–5). As mentioned before, long-term seasonal effects can be observed in the observed time series. During winter months, the soil CO_2 flux values are somewhat higher than during summer time for the concomitant effects of low barometric pressure and intense rainfall, which determine increases in the gas flux. These long-term effects are mainly observed at GFUR1 and GFOG1 stations, where a four-year-long data acquisition allowed better verify variations between summer and winter season (Fig. 6A). After filtering the flux data series, these seasonal variations seem to vanish (Fig. 6B), which is also an evidence of the goodness of the regression models applied. At GFUR1 and GFUR2 series it is possible to observe several months with the monthly average of the residuals near zero, which constitute an indication of the similarity between observed and *predicted* values.

Some variables, as the rainfall and the soil water content, mask the influence of all other monitored variables when responsible for significant short-term fluctuations (spike-like changes) on the gas flux. Fig. 5A shows the spiky response of the gas flux (for example, an increase of at least four times) to high rainfalls periods at GFUR1 station. It must be considered that the same adverse meteorological conditions that cause increases in the gas flux at the permanent stations may cause indoor CO_2 increases in some dwellings, representing a serious problem for the public health. In fact, CO_2 concentration up to 22.8%vol. (Fig. 7) was recorded in a dwelling during a sharp decrease on the barometric pressure. During almost 2 months of data acquisition, it is possible to observe spike-like increases in the indoor CO_2 concentration concomitant with the bad weather conditions, characterized by low barometric pressure periods, calling the attention to the permanent risk that the population may be exposed in volcanic areas (Viveiros et al., in press).

Even if some correlation coefficients between the observed and *predicted* values are low, in a general way the observed and the *predicted* plots for the soil CO_2 flux at GFUR1 and GFUR2 stations (Figs. 3 and 4) seem to behave similarly, meaning that the regression models proposed for this stations are appropriate to explain the gas flux behaviour. The Pearson correlation factor is sensitive to extreme values and some few periods of differences between the *predicted* and the observed datasets are enough to cause significant decreases on the correlation coefficients. In the case of GFOG1 station, and as it was previously mentioned, there are several discrepancies between the observed and the *predicted* values. There is some difficulty in proposing a model to this dataset due to other external unmonitored influences, as it is the case of the activities related with the geothermal power plant that may affect the gas flux. It is also possible to observe a decreasing trend in the residuals after May 2005, pointing out to anthropogenic influences. A new geothermal power plant started to be built in Pico Vermelho area and the works of ground remobilization around the permanent station were probably responsible for those decreases. For this reason, GFOG1 station was removed in April 2006 and reinstalled in an adjacent area with more stable environmental conditions. This aspect also calls out our attention to the fact that it is necessary to know all the changes that occur on the surroundings of the stations, otherwise one can misunderstand the gas flux variations.

After filtering the raw data from the meteorological influences, the *residuals* may highlight variations in the gas flow from depth. For this, it is necessary to compare the filtered dataset with time series obtained by other monitoring techniques, as the geophysical and geodetic measurements. Several authors (e.g. King 1993; Salazar et al., 2002; King et al., 2006) detected geochemical anomalies related with seismic activity. In this study case, it was not possible to establish a direct relation between the soil CO_2 flux and the seismic and/or volcanic activity, which may be explained by the low magnitude of the earthquakes registered in the area, mainly during the 2005 Fogo volcano seismic crisis. Even in the regression model proposed to GFOG1 station, the number of seismic events was included as an independent variable, but they showed no significance with the soil CO_2 flux.

6. Conclusions

Soil CO_2 flux in quiescent volcanoes can show significant variations related mainly with meteorological influences. Spike-like oscillations are observed at permanent stations of Furnas and Fogo volcanoes, usually associated to bad weather conditions, mostly high rainfall periods and significant decreases in barometric pressure. These responses of the gas flux are almost immediate and can be attributed to the peculiarity of each location, such as topography, exposure, drainage area and soil fracturation.

Long-term oscillations are also observed in some soil CO_2 flux datasets and are mainly related with seasonal effects. The gas flux at each monitoring site behaves differently and is controlled by different meteorological variables, revealing the importance of defining the baseline behaviour for the soil CO_2 flux in every site. It is also recommended to install the soil flux permanent stations in areas without anthropogenic influences, since any activities on the environment around the stations may cause significant changes on the gas flux baseline behaviour. Understanding and filtering all of these relationships is fundamental for a correct seismic and volcanic monitoring in order to not misunderstand external meteorological influences with deep processes.

Acknowledgements

The authors would like to thank Giorgio Virgili, from the WestSystems, for his technical support. We wish also to acknowledge Dr. Paulo Amaral for his suggestions and discussion about soil mechanics.

This work was performed in the scope of the European Project “VOLUME — Understanding Subsurface Mass Movement” (FP6-2004-Global 3 — 018471). Fátima Viveiros is supported by a PhD Grant from Fundo Regional da Ciência e Tecnologia, Açores (M3.1.2/F/017/2007). The authors acknowledge Dr. Jeniffer Lewicki and an anonymous reviewer for their suggestions that greatly improved an earlier version of the paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jvolgeores.2008.07.005.

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