Parametric and spectral analysis applied to soil CO_2 flux time series
Application to seismovolcanic monitoring in the Azores archipelago

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Abstract

Soil CO2 diffuse degassing studies have become more important for volcano monitoring in the last two decades. These types of studies are particularly important during quiescent periods of volcanic activity, as is the case with the volcanoes located in the Azores archipelago. Eight permanent soil CO2 flux stations were deployed by CIVISA/IVAR on four islands covering five volcanic systems. The CO2 flux measurements are done once every hour and follow the accumulation chamber method. The stations are also equipped with sensors that simultaneously measure environmental parameters, since these external variables can influence the variation of the CO2 flux. Some of these variables, such as air temperature or atmospheric pressure, have a periodic behaviour that can be detected via a spectral analysis. This analysis shows, at some locations, a twenty-four hour periodic behaviour in CO2 flux.

To quantify the influence of the environmental variables on the CO2 flux, a stepwise multivariate regression was used. The variables with the least influence were removed (< 0.005 significance), and a model was constructed using the reminder variables. The regression models obtained show that between 18% and 51% of the CO2 flux variation can be explained by the effect of those variables.

The residual time series, calculated using regression models and the observed CO2 time series, represent the deep CO2 flux signal, and based on that, can be used to potentially detect periods of unrest in the volcanic systems and throw early warning alerts for an eventual reactivation of the volcanic system. These regressions models have been applied to the time series of five stations from IVAR/CIVISA on a near real-time automatic monitoring system.

1. Methodology

The CO2 flux measurement is made once every hour using the “time 0, depth 0” accumulation chamber method by Chiodini et al [1]. It is calculated as the slope of the best linear fit to the concentration curve over a period of time. At the same time, measurements of environmental parameters are collected. A period of more than one year of the collected data was chosen to build the models through the stepwise multivariate linear regression method. Spectral analysis was also applied to detect if the flux and which environmental parameters have a periodic behavior.

2. Spectrum Analysis

Spectrum analysis involves transforming a time-domain function into frequency domain. It can be preformed by applying a Discrete Fourier Transform or a Continuous Wavelet Transform of a discrete sequence with a wavelet function ψ.

- Discrete Fourier Transform is given by

$$H_k = \sum_{n=0}^{N-1} h_n \, e^{-i2\pi kn/N}$$

- Continuous Wavelet Transform of a discrete sequence is defined as [2]

$$W_n(s) = \sum_{n'=0}^{N-1} h_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s}\right]$$

3. Multivariate Linear Regression

Can be used when there is the need to explain the relationship between one dependent variable and two or more independent variables. Is advisable to chose independent variables that [3],

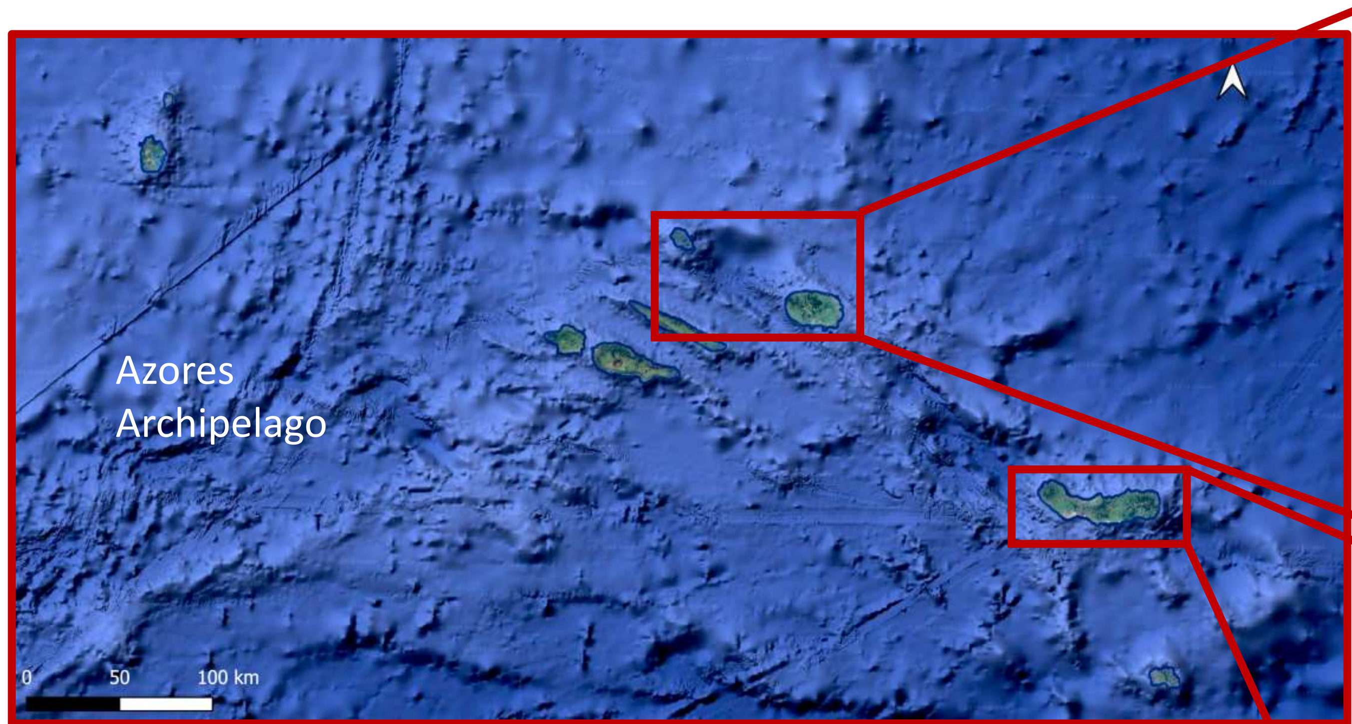
- Make the model as complete and realistic as possible, so an adequate prediction is possible.
- Include only the relevant variables because the irrelevant ones decreases the precision of the predicted values.

The model will have the following form,

$$y = \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \varepsilon$$

Where β_n are the coefficients, x_n the measured environmental factors and y the expected CO_2 flux. To determine the relevant variables, it tested the hypothesis that the coefficient's value is zero. P-values for all coefficients are determined, and those over 0.05 are rejected.

4. Study area

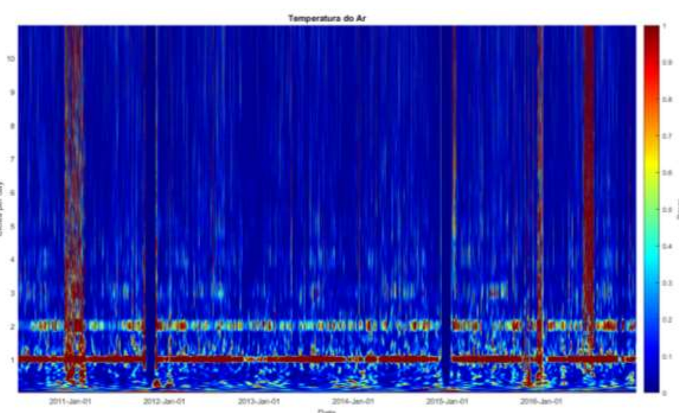


The study area was in Fogo and Furnas volcanos in São Miguel island, with two flux stations each, Pico Alto volcano in Terceira Island and Caldeira Volcano in Graciosa Island, both with one station each.

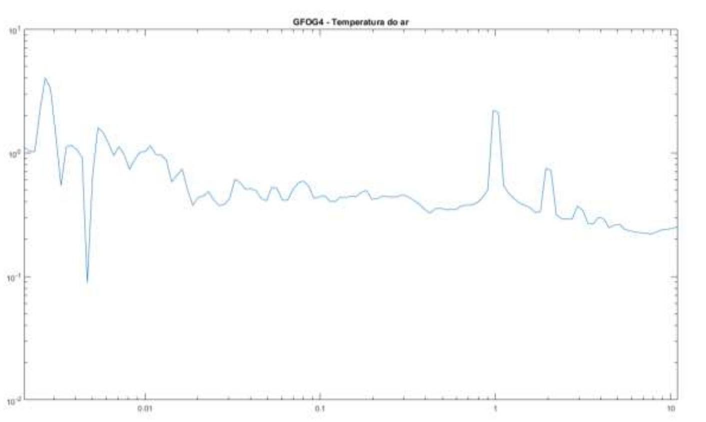
A side study was also conducted following the eruption of the La Plama volcano in the Canary Islands. Four sensors monitored the concentration of CO_2 in the air both inside (Sensors 2, 3 and 4) and outside (Sensor 1) buildings in the village of Porto Naos. The measurements where made using a costume made sensor pack.

5. Results

Azores Archipelago



Spectrum analysis of air temperature in GFOG4 using wavelets where is possible to view one cycle per day



Spectrum analysis of air temperature in GFOG4 using Fourier Transform where is possible to view one cycle per day

Table 1: Cycles per day for the environmental variables and for CO_2

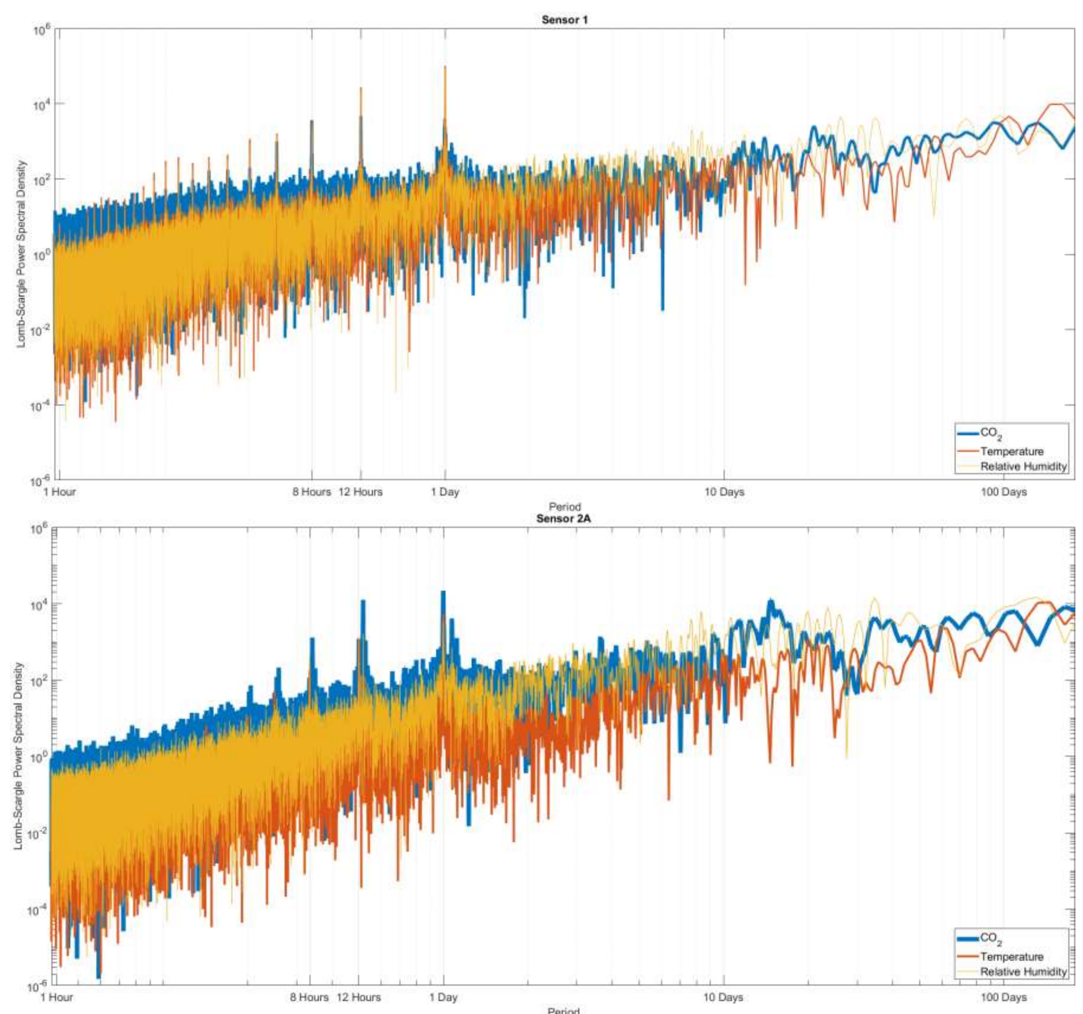
Station	T_{air}	RH_{air}	P_{atm}	T_{soil}	W_{soil}	CO_2
GFOG3	1	1	2	--	--	1
GFOG4	1	1	2	1	1	1
GFUR2	1	1	2	0	0	1
GFUR3	1	1	2	1	1	1
GTER1	1	1	2	1	0	1
GGCR1	1	0	1	0	0	1

Table 2: Models obtained by applying a stepwise linear regression. Adj. R^2 is the adjusted R squared

Station	Model	Adj. R^2
GFOG3 [4]	$q^{CO_2} = -2390 + 13.74 * T_{Air} + 2.73 * P_{atm} - 4.41 * T_{soil} + 9.69 * W_{soil} - 37.42 * V_{wind}$	41 %
GFOG4 [5]	$q^{CO_2} = 1508.5 + 53.99 * T_{Air} - 86.28 * T_{soil} + 85.88 * W_{soil} - 268.8 * V_{wind}$	47 %
GFUR2 [4]	$q^{CO_2} = -1555.3 - 8.17 * T_{Air} + 1.41 * P_{atm} + 20.28 * SoilT + 26 * W_{soil} - 0.64 * W_{soil}^2 - 10.92 * V_{wind}$	40 %
GFUR3 [4]	$q^{CO_2} = 2029.35 - 2.96 * T_{Air} - 2.11 * P_{atm} + 24.96 * T_{soil} - 0.28 * T_{soil}^2 - 28.08 * V_{wind}$	42 %
GTER1	$q^{CO_2} = 2123.9 - 7.34 * T_{Air} - 2.58 * P_{atm} + 23.35 * W_{soil} + (\sin(D_{wind} * 0.02) * 5.9 - \cos(D_{wind} * 0.02) * 4.03) * V_{wind}$	54 %
GGCR1	$q^{CO_2} = -63993 - 324.95 * T_{Air} + 48.56 * P_{atm} + 833.7 * T_{soil} - 18.425 * W_{soil}$	51 %

Where T_{air}: air temperature; RH_{air}: air relative humidity; P_{atm}: atmospheric pressure; T_{soil}: soil temperature; W_{soil}: soil water content; V_{wind}: wind speed; D_{wind}: wind direction

La Palma



An example of the results from La Palma. Spectrum analysis for air Temperature, Relative Humidity and CO_2. Sensor 1 is an outdoor sensor and Sensor 2 is indoors. Can clearly see the influence of the environmental variables in the concentration of air CO_2

6. Conclusions

Environmental variables account for about half of the variation in soil CO2 fluxes measured at the monitored sites. This relevant association between gas fluxes and external factors has already been demonstrated in various degassing regions throughout the world, therefore filtering the data is critical to identifying variations that may represent deep volcanic or hydrothermal activities. The statistical methodologies used appear appropriate for modulating the influence of environmental variables in soil CO_2 flux time series. La Palma study showed that air CO_2 can also be affected by these environmental factors.

References

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