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Anomalous Diffuse CO_2 Emission prior to the January 2002 Short-term Unrest at San Miguel Volcano, El Salvador, Central America

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Abstract—On January 16, 2002, short-term unrest occurred at San Miguel volcano. A gas-and-steam-ash plume rose a few hundred meters above the summit crater. An anomalous microseismicity pattern, about 75 events between 7:30 and 10:30 hours, was also observed. Continuous monitoring of CO_2 efflux on the volcano started on November 24, 2001, in the attempt to provide a multidisciplinary approach for its volcanic surveillance. The background mean of the diffuse CO_2 emission is about 16 g m^{-2} d^{-1}, but a 17-fold increase, up to 270 g m^{-2} d^{-1}, was detected on January 7, nine days before the January 2002 short-term unrest at San Miguel volcano. These observed anomalous changes on diffuse CO_2 degassing could be related to either a sharp increase of CO_2 pressure within the volcanic-hydrothermal system or degassing from an uprising fresh gas-rich magma within the shallow plumbing system of the volcano since meteorological fluctuations cannot explain this observed increase of diffuse CO_2 emission.

Key words: San Miguel, volcanic activity, diffuse degassing, carbon dioxide.

Introduction

The symmetrical cone of San Miguel, one of the most active volcanoes in El Salvador (Central America) rises from near sea level to 2,132 meters of elevation. This basaltic volcano is located in the eastern part of the country and lies on the southern fault of the Central American graben at the intersection with NW-SE trending faults (Fig. 1). San Miguel volcano has erupted at least 30 times since 1699, all events classified with a VEI of 1 or 2. Many of the earlier eruptions occurred at flank vents, but since 1867 all have taken place at the summit (MEYER-ABICH, 1956; SIMKIN and SIEBERT, 1994). San Miguel volcano has had active fumaroles in the summit region at

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least since 1964, and their variable intensity sustains usually a faint plume emitted from its summit crater. Since 1970, weak explosions took place four times, the last in January 2002 (GVN Bulletin, 2002).

The January 2002 short-term volcanic unrest at San Miguel was characterized by the emission of a gas-and-steam plume of 100 metric tons/day of sulfur dioxide containing a slight amount of ash rising with a mushroom-like profile a few hundred meters above the summit crater of San Miguel (GVN Bulletin, 2002). In addition, the event was accompanied by anomalous microseismicity with about 75 events between 7:30 and 10:30 hours, on January 16, 2002. This seismic swarm was followed by progressively decreasing seismic activity during the next days. This style of increased seismicity and gas emission is within the range of normal activity at San Miguel according to SNET (Servicio Nacional de Estudios Territoriales; the National organization in-charge of the volcano monitoring at El Salvador) since intermittent periods of vigorous steam-and-gas emission from San Miguel have been commonly reported in recent years (GVN Bulletin, 2002). The population at risk from a San Miguel eruption with significant ashfall is a mix of urban and rural residents. The city of San Miguel, at the foot of the NE flank of the volcano, has a population of ~150,000, and the rural zone that would likely be affected has a population of ~100,000 (GVN Bulletin, 2002).

Figure 1
San Miguel volcano located in the eastern part of El Salvador, Central America. Closed triangules represent those active volcanic systems with a continuous geochemical monitoring station of CO_2 efflux.

Scientists have long recognized that gases dissolved in magma provide the driving force of volcanic eruptions, but only recently geochemical techniques permitted continuous measurement of different types and manifestations of volcanic gases released into the atmosphere. Carbon dioxide is the major gas species after water vapor in both volcanic fluids and magmas and it is an effective tracer of subsurface magma-degassing, due to its low solubility in silicate melts (GERLACH and GRAEBER, 1985). Since this degassed CO_2 travels upward by advective-diffusive transport mechanisms and manifests itself at the ground surface, soil CO_2 efflux pattern changes over time provide information about subsurface magma movement (HERNÁNDEZ *et al.,* 2001a; CARAPEZZA *et al.,* 2004).

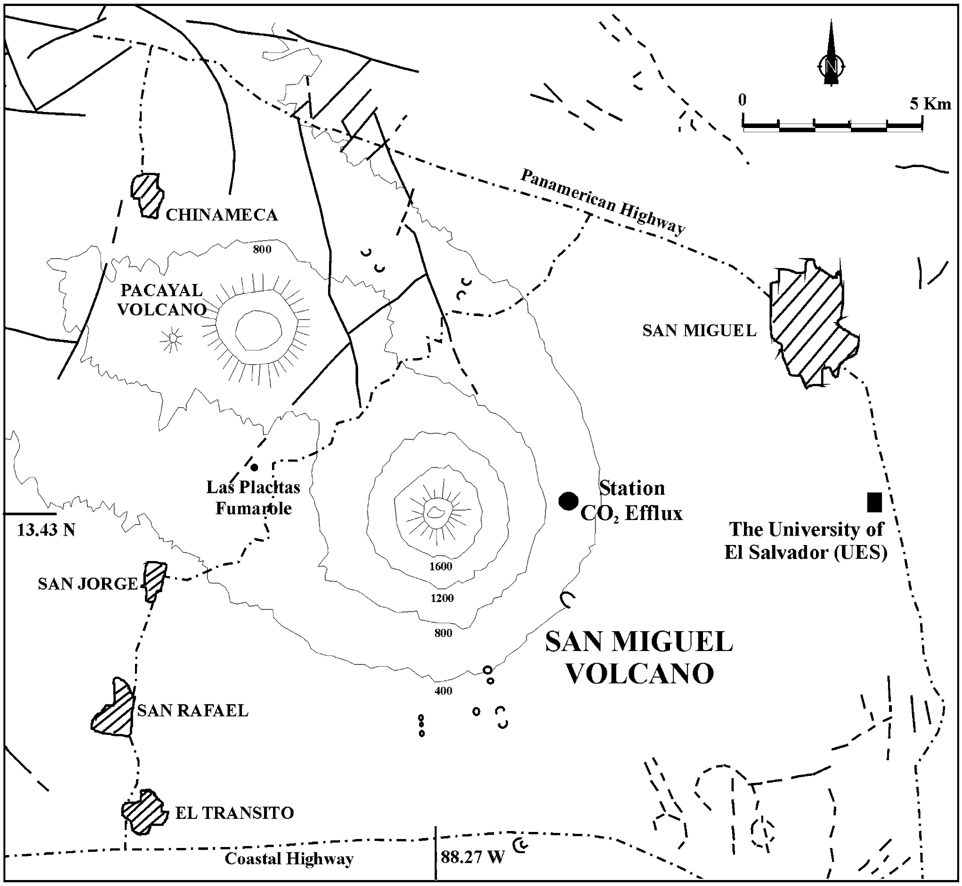

Figure 2
Simple morphological and structural map of San Miguel volcano and its surroundings. This map shows major inhabited areas in the well as the location of the Las Placitas' fumarole and the geochemical station (closed circle). Solid lines represent faults and dashed lines represent inferred fault systems. Dotted lines represent major highways.

Extensive work on diffuse CO_2 degassing has been performed at volcanic and geothermal areas over the last 13 years, suggesting that even during periods of quiescence, volcanoes release large amounts of carbon dioxide in a diffuse form (BAUBRON *et al.,* 1990; ALLARD *et al.,* 1991; FARRAR *et al.,* 1995; CARTAGENA *et al.,* 2004; CHIODINI *et al.,* 1996, 1998; HERNÁNDEZ *et al.,* 1998, 2001b; GERLACH *et al.,* 1998; SOREY *et al.,* 1998; GIAMMANCO *et al.,* 1998; PÉREZ *et al.,* 1996, 2004; ROGIE *et al.,* 2001; SALAZAR *et al.,* 2001). However, few works related to continuous monitoring of the diffuse CO_2 degassing have been published (ROGIE *et al.,* 2001; SALAZAR *et al.,*2002, 2004; MORI *et al.,* 2002; GRANIERI *et al.,* 2003; CARAPEZZA *et al.,* 2004; BRUSCA *et al.,* 2004).

Conventional geophysical methods are operating for the volcano monitoring program of San Miguel (e.g., volcano seismicity). In order to provide a multidisciplinary approach to volcanic surveillance of San Miguel, the Spanish Aid-Agency (AECI) provided the financial-aid to set up a geochemical station for the continuous monitoring of diffuse CO_2 degassing. Similar monitoring stations were installed at Santa Ana-Izalco-Coatepeque, San Salvador and San Vicente volcanic systems in 2001.

Procedures and Methods

With the aim of detecting anomalous temporal variations in diffuse CO_2 emission rates related to changes of volcanic activity at San Miguel, an automatic geochemical station (WEST Systems, Italy) was installed on November 24, 2001. This station continuously monitors diffuse CO_2 degassing on the eastern flank of San Miguel volcano (594 m a.s.l., Fig. 2). The station is equipped with an on-board microcomputer as well as sensors to measure the air CO_2 gas concentration, wind speed and direction, air temperature and relative humidity (1 m above the ground). The accumulation chamber is lowered on to the ground for several minutes every hour, and during this period the gas is continuously extracted from the chamber, sent to the IR spectrophotometer, and then injected again into the chamber. The latter is equipped with a mixing device in order to improve gas mixing. Soil CO_2 efflux is then measured according to the accumulation chamber method by means of a NDIR (non-dispersive infrared) spectrophotometer (Dräger Polytron IR transmitter) with a double-beam IR detector with solid state sensor compensated in temperature. Accuracy of 3% is acquired for a reading at 350 ppm. The automatic geochemical station is powered with a solar cell panel and a backup battery. Values of CO_2 efflux ($g\ m^{-2}\ d^{-1}$) are estimated from the rate of concentration increase in the chamber at the observation site, accounting for changes of atmospheric pressure and temperature to convert volumetric concentrations to mass concentrations. The chamber rim is designed to be set properly on the ground in order to eliminate the input of atmospheric air, which could cause significant errors, especially on windy days. The reproducibility for the range 10–20,000 $g\ m^{-2}\ d^{-1}$ is ±10%. We assumed a random

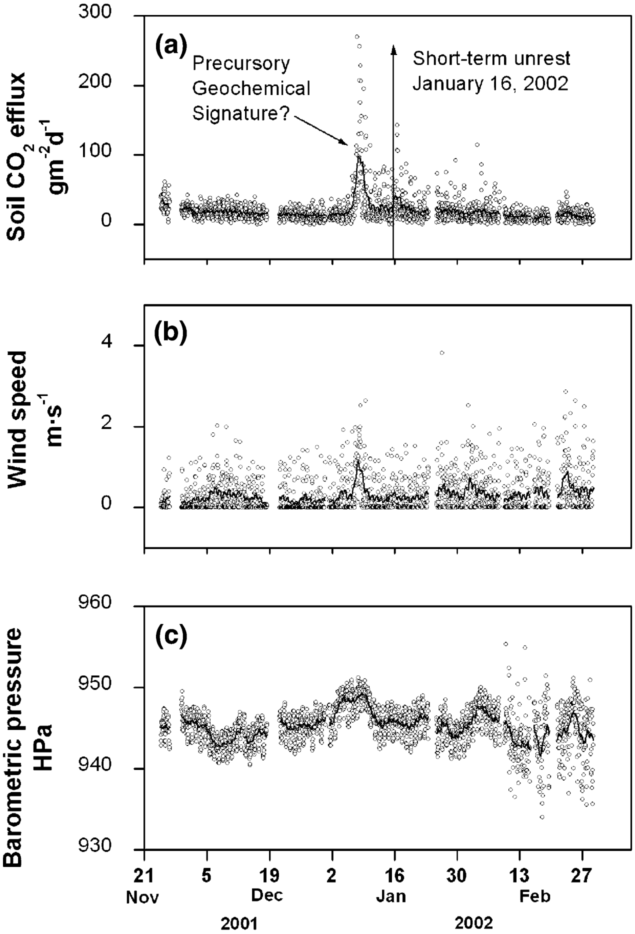

Figure 3
Time series of (a) diffuse CO$_2$ emission rate, (b) wind speed and (c) barometric pressure on the eastern flank of San Miguel Volcano from November, 2001 to March, 2002.

error of ± 10% in the emission rates of CO$_2$, based on variability of the replicate measurements carried out on known CO$_2$ efflux rates in the laboratory. All measurements were performed during the dry season in El Salvador.

Results and Discussion

A time series of 2,326 hourly observations of diffuse CO$_2$ emission rate, wind speed and barometric pressure from 17:00 hours of November 24, 2001, to 14:00 hours of March 1, 2002, as well as their moving averages of 36 hours are shown in Figure 3. A total of 12.4% of missing data throughout the observation

Table 1

Summary of results from the geochemical station at San Miguel Volcano

CO_2 efflux (g m^{-2} d^{-1})	Range	<0.25–270
	Mean	29.4
	Std deviation	33.2
Air relative humidity (%)	Range	12.5–97.3
	Mean	54.2
	Std deviation	19.3
Air temperature (°C)	Range	15.9–34.5
	Mean	23.9
	Std deviation	4.2
Bar pressure (hPa)	Range	932.1–959.0
	Mean	945.3
	Std deviation	2.7
Wind speed (m s^{-1})	Range	0.0–13.7
	Mean	1.1
	Std deviation	1.6
Wind direction (°)	Range	0.8–341.7
	Mean	202.1
	Std deviation	90.5
Tidal ( )	Range (x1000)	−999.3–2241.7
	Mean (x 1000)	189.7
	Std dev (x1000)	754.2

period occurred due to telemetry problems. The effect of the missing data on the overall data set is not likely to produce spurious correlation results because most of the missing data were recorded when diffuse CO_2 degassing on the eastern flank of San Miguel volcano was stationary. Table 1 summarizes the result of the CO_2 efflux data and the observed external variables.

The observed diffuse CO_2 emission data ranged from negligible values up to 270 g m^{-2} d^{-1}. These time series may be separated into four distinct set intervals: (i) from the beginning of the observation until January 6, 2002, characterized by a low variance of the CO_2 efflux and relatively low diffuse CO_2 emission rates of about 16 g m^{-2}, d^{-1}; (ii) from January 6 to 16, 2002, characterized by a short-term transient in the soil CO_2 degassing emission $\sim$ 9 days before the short-term unrest with CO_2 efflux values reaching up to 270 g m^{-2} d^{-1}; (iii) from January 16 to February 9, 2002, characterized by wider scatter of efflux data and a relatively high CO_2 efflux value (143 g m^{-2} d^{-1}) occurring at the onset of an anomalous seismic pattern at San Miguel volcano in January 16, 2002, and (iv) a period from February 9 to March 1, 2002, characterized by CO_2 efflux values similar to those observed within period (i).

Wind speed values ranged from 0 to 3.8 m/s. Average wind speed was 0.18 m/s. However, wind speed time series showed a simultaneous increase with the transient of soil CO_2 efflux in period (ii). Barometric pressure ranged from 938 to 949 HPa within periods (i) to (iii). Barometric pressure time series reflected the passing of low

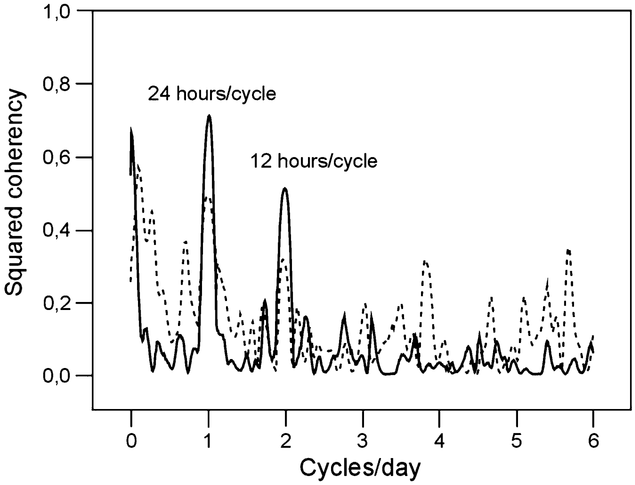

Figure 4
Cross-spectral analysis of the soil CO_2 efflux and wind speed (solid line) and soil CO_2 efflux and barometric pressure (dashed line) time series.

and high pressure fronts over the observation site. A high pressure atmospheric regime started on January 2 and ended January 12, 2002. Both wind speed and barometric pressure displayed high values during period (ii), where a short-term transient in the soil CO_2 degassing was observed. These observations drive the question whether wind speed and/or barometric pressure may be responsible for the observed changes in the soil CO_2 degassing at San Miguel volcano. At this aim, time domain classical techniques were applied to get the autocorrelation functions of the three original time series, showing the presence of cycles of the same length.

Because various types of serial dependence (trends, cycles, and autoregressive serial dependence) within time series can give rise to spurious or misleading correlations between time series (WARNER, 1998), soil CO_2 efflux, wind speed and barometric pressure time series were standardized and prewhitened before spectral analysis was performed. Soil CO_2 efflux time series was log-transformed and differenced one time to obtain a much more stationary time series. Wind speed and barometric pressure time series only required one order differencing before getting stationarity. Then spectral coherences between the prewhitened soil CO_2 efflux and wind speed, as well as soil CO_2 efflux and barometric pressure time series were computed (Fig. 4). Cross-spectral analysis of the prewhitened time series shows that a high percentage of shared variance between both sets of time series occur at one and two cycles per day, which correspond's to periods of 24 and 12 hours, respectively, suggesting a causal influence or coupling of wind speed and barometric pressure on the observed soil CO_2 efflux values at diurnal and semi-diurnal frequencies. These results suggest a close relationship between the temporal variations of the soil CO_2 efflux and those of meteorological variables, showing

24- and 12-hour periodicities (i.e., wind speed, barometric pressure, solar radiation, air temperature, etc.).

Once the main cyclic components of the prewhitened soil CO_2 efflux time series have been identified, it was possible to model the original soil CO_2 efflux signal using the harmonic analysis (Fig. 5a), based on the following equation

$$\Phi(t) = \mu + \sum_{i=1}^{2}\{A_i \cos(\varpi_i t) + B_i \sin(\varpi_i t)\} + \varepsilon,$$

where $\Phi(t)$ and μ are the observed soil CO_2 efflux time series and its mean, respectively, ω_i (i = 1,2) are the main identified frequencies corresponding to the main periodic components of the soil CO_2 efflux signal, A_i and B_i are model

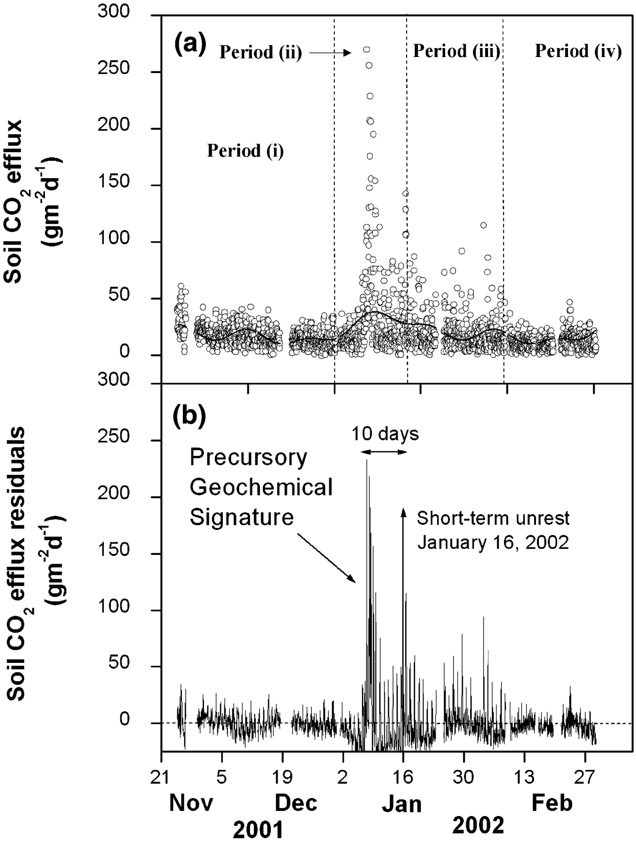

Figure 5

(a) Original soil CO_2 efflux signal (closed circles) and fitted harmonic model (solid line) with two major periodic components; (b) residual of harmonic analysis showing the persistence of a large amplitude transient in the soil CO_2 time series.

parameters to adjust during the fitting process, t is the observation time and, finally, ϵ are the residuals uncorrelated with the cos and sin terms. Using this simple deterministic model, the autoregressive behavior of the soil CO_2 efflux time series, which is linked to the periodic behavior of the meteorological variables (wind speed and barometric pressure), can be removed from the original soil CO_2 efflux signal. As a result of this filtering procedure, a large amplitude transient in the soil CO_2 degassing still remains within the residuals (Fig. 5b) temporally related with the onset of the anomalous seismic pattern at San Miguel volcano.

Low amplitude and almost universal short-term CO_2 efflux changes driven by meteorological fluctuations have been observed in others volcanic systems (SALAZAR *et al.,* 2000, 2002; PADRÓN *et al.,* 2001; ROGIE *et al.,* 2001; GRANIERI *et al.,* 2003). This significant transient increase of CO_2 efflux rate observed on January 6 and 7, 2002, cannot be explained in terms of meteorological fluctuations such as barometric pressure and wind speed temporal variations recorded at the station site.

Since meteorological fluctuations cannot explain the observed relative increase of the CO_2 efflux rate on January 6 and 7, 2002 (Fig. 3), it is evident that the observed changes of diffuse CO_2 emission rate on the eastern flank of San Miguel volcano should be related to either a sharp increase of CO_2 pressure within the volcanic-hydrothermal system or degassing from an uprising fresh gas-rich magma within the shallow plumbing system of the volcano as it was explained for the observed changes on CO efflux prior to the Stromboli 2002–2003 eruptive events (CARAPEZZA *et al.,* 2004; BRUSCA *et al.,* 2004). As an alternative procedure to isolate the joint impulse-response function of the CO_2 efflux and determine the effects of variations in the hydrothermal system on diffuse CO_2 efflux, we used multivariate regression analysis (MRA) to delineate the relations between CO_2 efflux and external factors and then use these relations to filter out the effects of these factors on the measured efflux history. In this case, we considered in the analysis the most relevant parameters to explain the variability of the CO_2 efflux, barometric pressure, wind speed, tidal, air temperature, air relative humidity, wind direction and power supply. MRA is commonly used to predict a dependent variable, y, as a function of relevant

Table 2

Stepwise forward results From the MRA analysis

	Multiple R	F to ENTER	p-level
Air temperature	0.132472	36.331	0.0000
TIDAL	0.178912	30.371	0.0000
Barometric pressure	0.191681	9.981	0.0016
Wind Speed	0.199183	6.201	0.0128
Power supply	0.200368	1.001	0.3170
Wind direction	0.200887	0.440	0.5071
Relative humidity	0.201147	0.221	0.6381

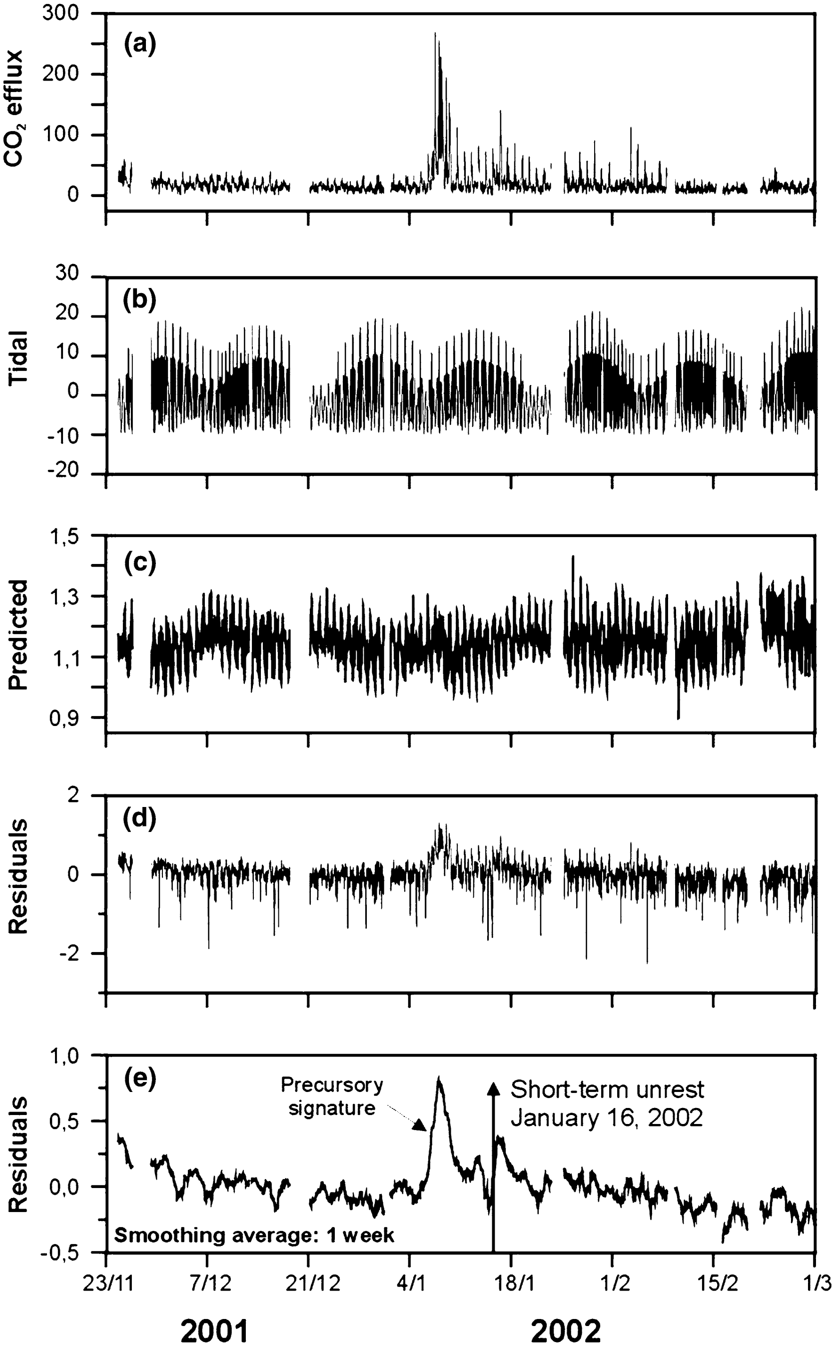

Figure 6
Observed (a) and predicted (c) CO_2 efflux time series of San Miguel Volcano. Figures 6d and 6e show the total residuals and smoothed residual of the MRA for the same data series.

explanatory variables, x1, x2,..., xn. Results of MRA provide an understanding of the percentage of the variability in y that is explained by the selected set of x variables. A forward stepwise regression analysis (Table 2) was performed to identify the most efficient set of x variables that would explain most of the variability in y and also to assess whether the relationship between y and the selected set of x variables is statistically significant, with the retained explanatory variables. A F to enter criterion of 1.0 and F to remove 0.0 for entering or removing an explanatory variable were used. The correlation coefficient (r) between the CO_2 efflux and each explanatory variable was calculated. The highest simple correlation was between the CO_2 efflux and air temperature ($r = 0.13$). The statistical significance level of the regression model (p value) was less than 0.0001 with air temperature and TIDAL as independent variables, indicating a highly significant model. The square of the multiple regression coefficients (r^2) for the regression equation was 0.20, which means that about 20% of the variability in the estimated CO_2 efflux is explained by the regression model. The time evolution of the residuals of MRA filtering is shown in Figure 6. Again, the filtered trend and residual components showed the anomalous increase on the diffuse CO_2 degassing 10 days before the onset of the short-term unrest at San Miguel volcano.

Fluid pressure fluctuations in volcanic systems might be also related to stress/strain changes in the subsurface due to either magma rising beneath the volcano or the occurrence of a relatively high magnitude earthquake in the vicinity of the volcano. The last rationale was recently described by SALAZAR *et al.* (2002) at San Vicente volcano (El Salvador, Central America) where significant CO_2 efflux rate fluctuations were measured relative to a 5.1 magnitude earthquake, which occurred to 25 km away from the observation site on May 8, 2001. A significant increase in CO_2 efflux rate was mainly driven by strain changes prior to this earthquake.

Since the seismic activity recorded in the vicinity of San Miguel volcano at the end of 2001 and early 2002 do not reflect the occurrence of a relatively high magnitude earthquake, magma movement at depth seems the most reasonable scenario for the observed increase on the diffuse CO_2 emission rate at San Miguel volcano on January 6 and 7, 2002. This geological phenomena should be responsible for a relative increment of the internal pressure of magmatic volatiles due to magma rising within the volcanic-hydrothermal system; therefore, driving an increase of diffuse CO_2 emission in the surface environment of San Miguel volcano prior to the observed vigorous steam-and-gas emission through the plume and microseismicity changes on January 16, 2002.

After the observed precursory geochemical signature of diffuse CO_2 emission rate at San Miguel volcano, period (iii), CO_2 efflux values showed a higher dispersion than those observed before January 6, 2002. This scattered behavior on the CO_2 efflux rate could mainly be due to long-period earthquakes, volcanic tremor, and explosion events which were recorded at San Miguel in late January and February (GVN BULLETIN, 2002).

Conclusions

An increase up to 17-fold the background mean value of diffuse CO_2 emission rate was observed before short-term unrest at San Miguel volcano on January 16, 2002. These CO_2 efflux changes were not driven by fluctuations of meteorological variables such as wind speed and barometric pressure and seem clearly associated to a relative increment of CO_2 pressure within the volcanic-hydrothermal system due to magma movement at depth beneath San Miguel volcano. These results showed the potential of applying continuous monitoring of soil CO_2 efflux to improve and optimize the detection of early warning signals of future volcanic crisis at San Miguel as well as in other active volcanic systems. Further observations, after fixing the radiotelemetry system are needed to verify the existence of a close relationship between diffuse CO_2 emission rate and volcanic activity.

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