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Continuous monitoring of fumarole temperatures at Mount Etna (Italy)

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ABSTRACT

In this paper we present the first data of temperature continuously recorded in two fumarole fields (designated VOR and HOR) located in the summit area of Mount Etna volcano (Italy). The time series embraces two distinct periods: (1) October 2007 to November 2009, during which an effusive eruption occurred from May 2008 to July 2009, and (2) November 2011 to June 2012, characterized by the occurrence of strong paroxysms (fire fountains and lava flow). The analysis of the temperature signal in both the time and frequency domains, and its comparison with meteorological observations allowed us to separate the exogenous influences from the effects of variations in the activity state of the volcano. The acquired data were weakly affected by seasonal cycles of the air temperature and strongly affected by the rainfall. Optimization of site conditions (i.e., sensor depth and soil permeability) markedly reduced meteorological disturbances. The distance from the main degassing and/or eruptive fractures was crucial to maximizing the probability of the technical survival of the monitoring apparatus, which was seriously affected by the emission of acidic gases, tephra fallout, and lava flows. Apart from the exogenous influences, the most appreciable variation was observed at VOR, where a huge increase in fumarole temperature was detected immediately after the onset of the 2008–2009 eruption. Such an anomalous increase was attributed to the rapid ascent of magma feeding the eruptive fracture. Another abrupt increase in temperature was recorded at HOR in March and April 2012. During this period the frequency of paroxysm occurrence increased markedly, and this led us to hypothesize that the thermal anomaly was due to the intrusion of a new batch of magma in the conduits of the southeast crater. Medium- to long-term monitoring (weeks to months) of fumarole temperatures revealed variations that were attributed to pressurization/depressurization phases of the shallow volcanic system, which varied between the various monitored sectors of the volcano. Our observations suggest that continuous monitoring of fumarole temperature can give useful information about the activity of Mount Etna. Moreover, due to the complexity of its shallow plumbing system, we conclude that the monitoring systems should be extended to cover the entire fumarole network of the summit area.

1. Introduction

One of the most exciting goals during the study of a volcanic system is the evaluation of the state of activity aimed to eruption forecasting; in doing this, the multi parametric approach is crucial to recognize and follow magma dynamics in the plumbing system. Moreover, a high-frequency data acquisition is essential to avoid the risk of missing information. As a consequence, volcanic monitoring has been mostly based on geophysical techniques. Indeed, gases released from volcanoes may be sampled and analyzed only discontinuously (e.g., Hirabayashi, 1986; Giggenbach and Goguel, 1989; Pecoraino and Giammanco, 2005; Martelli et al., 2008; Liotta et al., 2010, 2012; Paonita et al., 2012), because during eruptive periods or extreme meteorological conditions the approach of summit areas is very hazardous, allowing only an incomplete understanding of magma dynamics. In addition, the delay (from days to months) between sampling and analysis may represent a further issue to a timely evaluation, leading very often to an “a posteriori” assessment of activity state.

Only recently geochemical monitoring has been integrated with techniques that permit a high-frequency data acquisition of some parameters and it has been thus accepted by the scientific community as an essential tool to integrate geophysical background. One of the first applications regarded the routine monitoring of SO_2 flux from plume gases by remote sensing, which has allowed data acquisition at safe distances from summit craters and volcanic activity to be followed during eruptive periods. At Kilauea (Hawaii) SO_2 flux has been monitored since 1979 (Sutton et al., 2001), while in the following years these measurements have been extended to other volcanoes such as for instance Stromboli (Italy) (Allard et al., 1994), Mount Etna (Italy) (Caltabiano et al., 1994) and Soufrière Hills (Montserrat) (Young et al., 1998). Today this parameter is monitored nearly real-time in most of the volcanic systems located worldwide with more innovative techniques. The chemical composition of plume gases is routinely investigated by FTIR measurements, which allow to record remarkable short-period (seconds) variations, such as for instance at Stromboli

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(Burton et al., 2007). In addition, Aiuppa et al. (2007) have reported the first systematic set of simultaneous H_2O, CO_2 and SO_2 acquisition in the Etnean gas plume during the 2006 eruption. In the last decades, technological innovation has also concerned the investigation of chemical composition of gases released from fumaroles. It has started from the measurement of a single gas component, e.g. O_2 (Benhamou et al., 1988), SO_2 (Bluth et al., 1994) and Rn (Cigolini et al., 2001). From 1995 to 1998, Shimoike and Notsu (2000) have continuously monitored several components at Izu-Oshima (Japan) volcano; similar studies have been performed at Galeras (Colombia) (Faber et al., 2003), Merapi (Indonesia) (Zimmer and Erzinger, 2003) and Nisyros (Greece) (Teschner et al., 2007). Geochemical, volcanological, and geophysical observations have recently been mutually integrated, giving new insights on magma dynamics at considerable depths and permitting to assess the state of activity of a volcano with increasing reliability (e.g., Andronico et al., 2005; Caliro et al., 2005; Harris et al., 2005; Gottsmann et al., 2007; Aiuppa et al., 2010; Carniel et al., 2010; Cannata et al., 2011).

The investigation of chemical composition of volcanic gases may be coupled with continuous monitoring of fumarole temperature, because the latter is closely related to variations in the fluxes of deep and hot gases (e.g., Tedesco et al., 1991; Connor et al., 1993; Alparone et al., 2004; Brusca et al., 2004; De Gregorio et al., 2007; Rizzo et al., 2009; Cannata et al., 2011; Diliberto, 2011). In detail, when steam flux increases, as a consequence of an enhanced degassing during magma upraise toward the surface, a gradual and/or a sharp rise of fumarole temperatures may be recorded at the surface. The thermal anomaly may precede the onset of eruptive activity, as observed at Volcàn Poàs (Costa Rica) in 1980 (Barquero, 1983, 1988). On the contrary, when the discharge of volatiles reduces, it is reasonable to expect a decrease of fumarole temperatures, coherent with previous observations in other volcanic systems (Stoiber et al., 1975; Connor et al., 1993). Other precious information comes from thermal imaging. Calvari et al. (2004) obtained helpful results during the 2002–2003 eruptions of Mt Etna and Stromboli, individuating the opening of fissure systems related to the increasing volcanic activity. Thus, this parameter can be considered useful in evaluations of volcanic activity, even though anomalies caused by variations of the local tectonic stress field (via soil permeability changes) may interfere with the pure volcanogenic signal, as observed at Merapi (Indonesia) (Zimmer and Erzinger, 2003; Richter et al., 2004), at Stromboli (Italy) (De Gregorio et al., 2007) and at Vesuvius (Italy) (Madonia et al., 2008). Fumarole temperatures are also subject to changes due to exogenous causes, mostly connected to meteorological parameters that must be contemporarily monitored. Indeed, Connor et al. (1993) have demonstrated that barometric pressure has an inverse correlation with fumarole temperature and mostly affects low-temperature emissions also with a low mass flow. The direction and velocity of the wind may also change the fumarolic system, as observed by Faber et al. (2003) and Liotta et al. (2010), while rainfall is the most critical cause of temperature drops (e.g., Zimmer and Erzinger, 2003; Friedel et al., 2004; Richter et al., 2004).

At Mount Etna only few studies based on discrete temperature monitoring have been carried out. The greatest variations were observed during 1991–1994 by Bonfanti et al. (1996), who measured an increase in water temperature in springs and wells prior to the onset of the 1991–1993 eruption. Alparone et al. (2004) and Pecoraino and Giammanco (2005) performed discrete monitoring of low-temperature fumaroles located in the upper part of the volcano, but they found no clear correlation with volcanic activity. Finally, Liotta et al. (2010) studied the fluid circulation in the summit area for a few months by monitoring variations of a high-temperature fumarole near Voragine crater (hereafter called VOR).

In the present study we show the results of the first continuous monitoring of two low-temperature fumaroles located in the summit area of Mount Etna volcano during two distinct periods: (1) from October 2007 to November 2009 and (2) from November 2011 to May 2012. The former period was characterized by a new long-lasting eruption that occurred between May 2008 and July 2009, while the latter was characterized by frequent paroxysmal activity. We investigate how exogenous (i.e., meteo-astronomical) and endogenous (e.g., degassing and volcanic activity) parameters may influence fumarole temperature, both on short (hours to days) and medium (months) timescales, comparing thermal data with geodetic measurements recorded during the same period.

2. Methods and site descriptions

Soil temperatures were acquired hourly at depths of 10 and 30 cm by automated stations, based on Onset Microstation four-channel data loggers, each connected to two 12-bit digital temperature smart sensors from the same manufacturer. Sensors operate in the range −40 °C to 100 °C, with a resolution of 0.03 °C and an accuracy of ±0.2 °C. Temperatures were measured every 4 min and their hourly averages were stored in the permanent memory of the logger.

Two measuring sites (Fig. 1) were selected from among the locations compatible with safety conditions for the installation and maintenance of instruments, on the basis of geochemical investigations carried out in the summit area, but also considering the main active structures feeding soil degassing of magmatic fluids and recent eruptive activities.

The first measuring site is located at 3260 m a.s.l. on the northeastern inner rim of VOR, which is one of the central craters, and was monitored from October 2007 to November 2009. Previous geochemical studies were performed by Martelli et al. (2008) and Liotta et al. (2010, 2012) on a high-temperature fumarole (named F4, up to 500 °C) located close to our monitoring site. From these studies the composition of the fumarole — even though highly contaminated by air — was only slightly affected by postmagmatic processes (i.e., scrubbing and hydrothermal contributions), and thus reflected the degassing of pristine magmatic gases, like those characterizing the plume. In addition, Liotta et al. (2010) continuously recorded its temperature variations for a short period (July–September 2008), which revealed a relationship with wind speed due to the Venturi effect acting on the open steam-feeding cracks. To avoid this effect, we installed our data logger and thermal sensor at a small distance from the hottest fractures, where the exposed surface appeared coherent and unfractured, thereby protecting the system from damage due to acidic corrosion and overheating. Considering that the soil around the fumaroles is heated by steam discharged through advective degassing, the parameter we monitored was the steam-heated soil temperature (hereafter SHST).

The second site is located at about 3000 m a.s.l. next to the "hornitos" formed during the 1999 eruption (hereafter called HOR) and positioned south of the southeast crater (hereafter SEC). This fumarole field is located on the southeast rift that represents one of the main degassing fractures in the Etnean summit area, which has been known since the 1787 eruption and named "Vulcarolo" (Ponte, 1927; Aubert, 1999; Alparone et al., 2004). This field is covered by lava and tephra that has erupted from SEC since 1989, but its huge degassing has persisted over time. In the first decades of the 20th century the high steam flux from Vulcarolo has led to place a condenser in order to collect water for feeding the neighboring observatory (Ponte, 1927). Anomalous degassing from this fumarole field was identified by Alparone et al. (2004), who investigated the CO_2 concentration of soil along a transect crossing the main fracture. A preliminary study showed that the soil temperatures were generally below 90 °C, which is the boiling temperature of water at that altitude, and the gas is directly emitted through advective degassing. During our study HOR was monitored during two periods: from November 2008 to November 2009 and from November 2011 to May 2012; the data from December 2009 to October 2011 are missing because the first