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Validating gas dispersion modelling at La Solfatara (Campi Flegrei, South Italy)

S. Massaro([1])([2]), M. Stocchi([2]), G. Tamburello([2]), A. Costa([2]), L. Sandri([2]), S. Caliro([3]), G. Chiodini([2]), J. Selva([2]), F. Dioguardi([4])(*), A. Folch([5]) and G. Macedonio([3])

([1]) *Dipartimento di Scienze della Terra e Geoambientali, Università di Bari - Bari, Italy*
([2]) *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna - Bologna, Italy*
([3]) *Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano - Napoli, Italy*
([4]) *British Geological Survey, The Lyell Centre - Edinburgh, UK*
([5]) *Geosciencias Barcelona (GEO3BCN-CSIC) - Barcelona, Spain*

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Summary. — Probabilistic hazard assessments of volcanic gases need to account for the natural variability associated to aspects such as weather conditions, source location, emission rate, and gas species. In order to quantitatively carry out these assessments, computational tools for gas dispersal need to be validated to demonstrate the reliability of the model results. Here we provide an exemplificative gas dispersal model validation at La Solfatara (a maar crater within Campi Flegrei caldera) which hosts one of the largest and hazardous fumarolic sites of the world, by using a workflow designed for automating the simulation strategy for probabilistic gas hazard assessments. This represents the first fundamental step towards gas hazard quantification in the area.

1. – Introduction

In the last decades, density-driven and passive volcanic gas transport models have been largely employed in active volcanic areas for gas dispersal validations and for probabilistic volcanic hazard assessment (PVHA) applications (*e.g.,* [1, 2]). Since gas dispersal is controlled by multiple variables, PVHA should explore the natural variability in the input parameters, as wind conditions, source locations and emission rates, and gas species composition. This results in the need to perform numerous simulations. A previous work [2] validated the modeling of gas dispersal at La Soufrière de Guadaloupe (Lesser Antilles) through a simulation workflow, which has been recently implemented into the package VIGIL (automatic probabilistic VolcanIc Gas dIspersion

(*) Now at: Dipartimento di Scienze della Terra e Geoambientali, Università di Bari - Bari, Italy

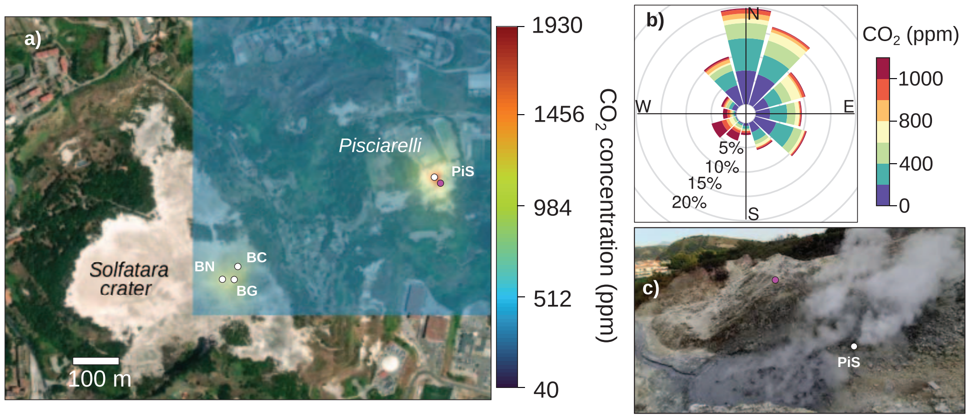

Fig. 1. – (a) Map of La Solfatara (Campi Flegrei; ©Maxbox), showing the fumarolic sources (BG: 427648 E, 4519920 N; BN: 427622 E, 4519924 N; BC: 427661 E, 4519933 N; PiS: 428084 E, 4520147 N; UTM WGS84 zone 33T) and the measurement station (428101 E, 4520143 N, purple dot). Overlaid the map showing the monthly averaged simulations of CO_2 concentration (ppm) at 4 m from the ground calculated within a domain of 650 m×650 m; (b) rose diagram of the June 2020 winds acquired by measurement station, showing the time frequency (in %) of the various directions of provenance of wind. In color shades we give the CO_2 concentration above background level. (c) Pisciarelli area, indicating the measurement station (purple dot) and the position of the fumarole (white dot), courtesy of G. Tamburello.

modeLing; v.1.2, `https://github.com/BritishGeologicalSurvey/VIGIL`). VIGIL is an open-source Python tool able to handle simulations in parallel and produce probabilistic output, using two Eulerian models: DISGAS (v.2.3 [3]) and TWODEE-2 (v. 2.3 [4]) which account for the passive and gravity-driven gas transport, respectively. The testing procedure proposed in [2] showed that the statistical properties of the natural variability displayed by the observed averages of CO_2 and H_2S concentrations is satisfactorily reproduced by simulations, confirming the workflow as key tool to produce unbiased hazard quantification. To corroborate these findings, validation of the gas dispersal models employed in PVHA application is necessary. Here, we present a validation study of the DISGAS model at La Solfatara (Campi Flegrei; fig. 1), which is currently affected by a persistent passive degassing (fumarolic and diffusive contributions show the Richardson number <0.25 [3]) within a densely populated area, opening the pathway for future short- to long-term PVHA [5, 6].

2. – Model validation

La Solfatara hosts an area characterized by a widespread soil release of CO_2. Significant amounts of CO_2 are also emitted by the most active fumarolic vents, located in the eastern slope (*i.e.*, Pisciarelli; PiS) and inside the Solfatara crater (Bocca Grande, BG; Bocca Nuova, BN; Bocca C, BC; fig. 1(a)). The validation of DISGAS is aimed to verify its forecasting capability with the observed CO_2 concentrations provided by the INGV measurement station (428101 E, 4520143 N; fig. 1(a)) during June 2020.

2˙1. *Model setup and inputs.* – To do this, we performed a 1-month-long simulation of dilute gas emission and dispersal using DISGAS by means of VIGIL. Since the passive condition at sources is verified at La Solfatara (*e.g.*, [7]), the gas plume is modelled on

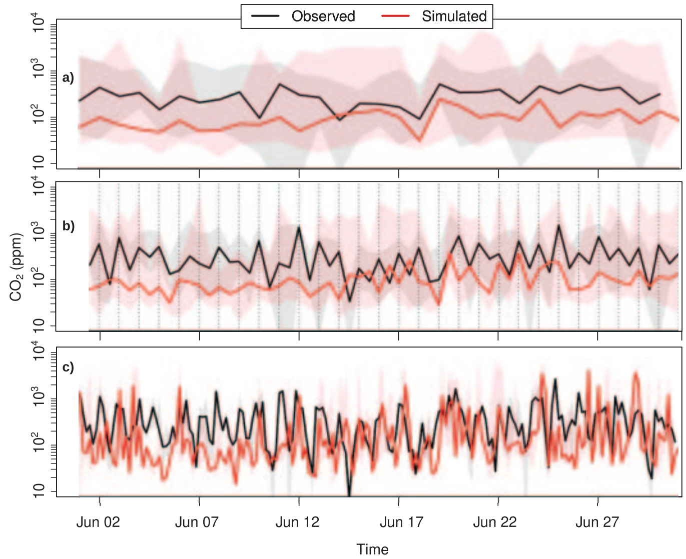

Fig. 2. – Observed (black line) and simulated (red line) average CO_2 concentrations (ppm) at 4 m from the ground for June 2020 performed using VIGIL: (a) daily averages; (b) 12-hour averages. Black dotted lines correspond to midnight time; (c) 4-hour averages. In each panel, the colored shaded bands represent the 90% confidence interval. A $\log_{10}$ scale is provided for the CO_2 concentration.

a computational domain of 650 m × 650 m with a horizontal resolution of 2.5 m × 2.5 m (fig. 1(a)). The topography is represented by a 1 m resolution DEM [8] resampled with grid spacing of 2.5 m. As weather data, we consider the daily local wind conditions acquired by the meteorological sensor placed on the INGV measurement station (fig. 1(a)) at 4 m above the ground. Since weather data are acquired every 2 hours while the mass-consistent diagnostic wind model included in DISGAS requires a sample each hour, we interpolated the wind field at time steps of 1 hour. The diffusive gas sources are simulated by discretizing in the emission area the total constant emission of ca. 6.7 kg s^{-1} (similarly to the maximum emission of CO_2 in 1999 [9]), along with the fumarolic sources: PiS (6.94 kg s^{-1} [10]) and BG, BN, BC (ca. 3.22 kg s^{-1}; scaled value from [11] and [10]). The simulated and observed concentrations were compared at 4 m above the ground considering that the weather measurements are referred to that height.

2·2. *Results.* – In fig. 1(a) we report the monthly average of the simulated CO_2 concentrations within the computational domain, showing values less than 5000 ppm, which is the time weighted limit for humans' health (8 h/day for 5 days a week [12]). In fig. 2 we compare the observed and simulated CO_2 concentrations, providing the daily (fig. 2(a)), 12-hour (day: 6 a.m. to 6 p.m.; night: 6 p.m. to 6 a.m.; fig. 2(b)) and 4-hour (fig. 2(c)) averages of the observed (black line) and simulated (red line) CO_2 concentrations along with the confidence interval at 90% represented by the black and red shaded bands, respectively. Similarly to the wind data, the observations of CO_2 concentrations consist of 400 s averages (sample every 20 s) collected every 2 hours at 4 m above the ground; the simulations' averages are made on the time series of simulated concentrations at the same location and atmosphere level, with a time step of 1 hour. To quantify the agreement between simulated and measured CO_2 concentrations, we calculated the Pearson product-moment correlation with three time-averaging windows: at the significance level 0.05, the logarithm of the observed and simulated daily-averaged time series (fig. 2(a)) show a significant correlation (R: 0.49; p-value: 0.007; 30 samples). In addition, the simulated daily-average concentrations are always within the 90% confidence band of the measured data. Comparisons for shorter time intervals are likely affected by poor weather and concentration acquisition frequency (2 hours), which may strongly impact averages over few hours. However, this result may provide important clues for future developments. In particular, the 12-hour averages (fig. 2(b)) highlight that the concentrations simulated tend to underestimate the observations. An analysis of such a potential bias is the focus of ongoing research but it requires a field campaign with higher rates of data acquisition.

3. – Conclusions

The emission of volcanic gasses can affect air quality and threaten humans' health when the concentrations exceed species-specific thresholds. In this framework, a model validation is pivotal before applying a simulator for PVHA. Here, we tested the accuracy of DISGAS in providing realistic results at La Solfatara. Our results showed a good correlation between the daily simulated and observed averages of CO_2 concentrations at 4 m from the ground, in the selected point where concentration measurements are available. We observed that the simulated monthly-averaged concentration does not exceed the gas hazardous threshold limits although for shorter timescales (hours), which tend to show high peaks of concentrations, a higher data acquisition rate is needed for future investigation.

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