



Drone CO₂ measurements during the Tajogaite volcanic eruption

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Abstract. We report in-plume carbon dioxide (CO₂) concentrations and carbon isotope ratios during the 2021 eruption of Tajogaite volcano, island of La Palma, Spain. CO₂ measurements inform our understanding of volcanic contributions to the global climate carbon cycle and the role of CO₂ in eruptions. Traditional ground-based methods of CO₂ collection are difficult and dangerous, and as a result only about 5 % of volcanoes have been directly surveyed. We demonstrate that unpiloted aerial system (UAS) surveys allow for fast and relatively safe measurements. Using CO₂ concentration profiles we estimate the total flux during several measurements in November 2021 to be $1.76 \pm 0.20 \times 10^3$ to $2.23 \pm 0.26 \times 10^4 \text{ t d}^{-1}$. Carbon isotope ratios of plume CO₂ indicate a deep magmatic source, consistent with the intensity of the eruption. Our work demonstrates the feasibility of UASs for CO₂ surveys during active volcanic eruptions, particularly for deriving rapid emission estimates.

the emission rates of this gas from volcanic craters, diffuse sources and low-level hydrothermal sites has remained a major challenge (Fischer and Aiuppa, 2020). As a result, detailed CO₂ surveys have been conducted at just 5 % of volcanoes (Fischer et al., 2019).

The main contributions of this work are that, for the first time, we estimate CO₂ flux using direct in-plume CO₂ measurements rather than using in-plume CO₂ / SO₂ ratios combined with separately measured SO₂ emissions. The second major contribution is that we perform in situ gas sample return during a major volcanic eruption for carbon isotope measurements. We use the Dragonfly unpiloted aerial system (UAS) (Ericksen et al., 2022) to gather samples directly from the eruption plume (Fig. 1). The UAS transects the plume and employs an onboard infrared (IR) sensor to continuously obtain concentration readings. These readings are then used to estimate a 2D isotropic Gaussian concentration model (Eq. 1). In-plume wind velocity measurements in combination with the plume model allow us to estimate CO₂ flux (Eq. 2). While our technique has similarities to the “ladder traverse” technique utilizing large in situ sensing equipment mounted on a piloted fixed-wing aircraft (Werner et al., 2013), it has the obvious advantages of being much less costly, logistically less challenging and less hazardous. Since our approach extrapolates the shape of the plume, it requires far fewer plume transects. Crucially, the Dragonfly UAS does not use a combustion engine, which previous work has shown to contaminate CO₂ measurements and samples with jet-fuel-derived organic carbon (Fischer and Lopez, 2016). The resulting plume CO₂ concentration profile is used to guide

1 Introduction

Measurements of volcanic CO₂ emissions during eruptions are critical for understanding magma and eruption dynamics. CO₂ is a significant greenhouse gas (Arrhenius, 1896), and making measurement of CO₂ emissions is important for climate science. CO₂ gas is second only to water vapor in abundance in volcanic emissions (Giggenbach, 1996). Despite the significance and abundance of CO₂ in the Earth system in general and in magmatic systems in particular, measuring



Figure 1. A Dragonfly UAS returning from a CO₂ sample mission during the November 2021 eruption of Tajogaite volcano. The large volcanic ash plume is visible in the background and contains an invisible CO₂ plume, which was the mapping target of this drone.

the UAS to a productive sample return location of maximum concentration. Carbon isotope analyses of the samples reveal information, such as the CO₂ source, which is relevant to predicting the course of the eruption. We tested this technique during the 2021 Tajogaite volcanic eruption on the island of La Palma, Spain, and compared the resulting flux estimates to the traditional ground-based CO₂ / SO₂ ratio method. As we demonstrate, UASs provide a method for obtaining in-plume gas samples, concentrations and wind velocity measurements. Together these data allow for the determination of isotope ratios and estimation of CO₂ flux, furthering our understanding of volcano dynamics during an eruption and allowing for predictions of eruption intensity and duration. Our technique can be widely used at passively degassing and erupting volcanoes to obtain near-real-time CO₂ flux measurements to better constrain the global volcanic CO₂ budget and assess volcanic activity.

1.1 Related work

While global initiatives to directly determine CO₂ flux from biogenic sources, i.e., FLUXNET (Office of Science, 2023), have advanced our understanding of the surface carbon cycle, estimates of volcanic flux are to a large extent obtained by combining SO₂ flux measurements with observed CO₂ / SO₂ ratios (Fischer and Aiuppa, 2020). This approach relies on two separate sets of measurements utilizing a ground-based or space-based remote sensing technique to determine the SO₂ concentration of the volcanic plume and a direct sampling or sensing technique to determine the CO₂ / SO₂ ratio. In almost all cases, these two separate sets of measurements are not made simultaneously and result in intrinsic uncertainties in CO₂ flux estimates (Burton et al., 2013). CO₂ surveys have been performed using satellite-based approaches; for example, Johnson et al. (2020) performed CO₂ flux estimates of Kīlauea volcano in 2018. Their work utilized the Orbiting Carbon Observatory-2 (OCO-2) to measure the CO₂

emissions from the 2018 Kīlauea eruption. A measurement of $77.1 \pm 41.6 \text{ kt d}^{-1}$ was obtained during the 1 d of observations where conditions enabled the collection of consistent high-quality data. Cloud coverage and aerosol are the major inhibitors for obtaining consistent CO₂ data using OCO-2. In addition, the wind direction must be near perpendicular to the satellite's orbit path and the measurements must be made downwind from the plume. The OCO-2 16 d repeat cycle currently makes this method impractical for frequent, high-rate CO₂ flux measurements from erupting volcanoes, and the only other successful volcanic CO₂ emission study was by Schwandner et al. (2017) of Yasur in Vanuatu. Therefore, space-based CO₂ instruments require favorable atmospheric conditions and satellite positioning and are not yet feasible for volcano monitoring (Schwandner et al., 2017).

The value of UAS surveys of volcanic emissions was recognized by Xi et al. (2016), who surveyed passively degassing SO₂ at Turrialba volcano, Costa Rica, and estimated SO₂ flux. Other investigators have used UASs to measure plume SO₂ and collect plume trace gases (Rüdiger et al., 2018) or use miniDOAS (differential optical absorption spectroscopy) systems mounted on an unpiloted aerial vehicle (UAV) to obtain SO₂ fluxes (Stix et al., 2018). Recently UASs (unpiloted aerial systems) have been used to collect gas samples and measure gas compositions of volcanic plumes from passively degassing volcanoes in remote regions (Liu et al., 2020; Galle et al., 2021) and during the 2023 eruption of Litli Hrófur, Iceland, to obtain information on CO₂ degassing and related carbon isotope fractionation (Fischer et al., 2024)

Gerlach et al. (1997) and Werner et al. (2013) estimate plume CO₂ flux using the parsimonious assumption that plumes are uniform. They use the mean value to estimate the flux, whereas we use our observations in the field that support the hypothesis that plumes can be well modeled by Gaussian distributions. Our work relies on the assumption that a Gaussian model of the plume cross-section results in more accurate estimates of total flux.

Burton et al. (2023) surveyed emissions of the Tajogaite eruption in early October 2021. Their survey included SO₂ measurements by UAV that were used to infer CO₂ concentrations. Our work in late November complements the Burton et al. (2023) survey by providing additional information on the evolution of the eruption and using a different CO₂ flux estimation method that employs direct CO₂ measurements rather than CO₂ / SO₂ ratios. Our estimates of CO₂ flux taken a month later were lower than those of Burton et al. (2023).

1.2 Background

The island of La Palma is in Spain's Canary archipelago (Schmincke, 1982). The northern sector of the island hosts the oldest subaerial (on-land) volcanism, characterized by repeated large lateral edifice collapses (Day et al., 1999;

Acocella et al., 2015). Volcanism resulted in the formation of Garaffa and Taburiente and then moved southward to form Cumbre Vieja volcano, at the southern part of the island. This southern system represents the last stage in the geological evolution of the island of La Palma, as volcanic activity has taken place exclusively on that part of the island for the last 123 kyr (Carracedo et al., 1998). The most recent volcanic eruption of Cumbre Vieja is Tajogaite (2021) (Carracedo et al., 2001; Ward and Day, 2001), preceded by that of Teneguía in 1971 (Fernández et al., 2021) and San Juan in 1940 (Fernández et al., 2021; Albert et al., 2016). At 14:10 UTC on 19 September 2021 Tajogaite volcano erupted from a vent on the western side of the island of La Palma, in the vicinity of the Llano del Banco eruptive center of the San Juan eruption of 1949 (Instituto Geográfico Nacional, 2022). The eruption was forecast using seismic, geodetic and geochemical techniques by Spanish researchers who alerted the civil protection officials several days before the start of the eruption (De Luca et al., 2022). The monitoring network of diffuse CO₂ emissions on La Palma detected magmatic CO₂ several months before the eruption (Santana de León et al., 2022; Rodríguez-Pérez et al., 2022). This monitoring activity took advantage of extensive previous work characterizing diffuse CO₂ emissions on La Palma. This work provided key insights into the dynamics of magmatic CO₂ degassing on the island (Padrón et al., 2015). The eruption itself began with an explosive phase that ejected ash to an altitude of 5 km, then transitioned to fire fountains, violent strombolian activity and the production of highly fluid lava flows. Within 24 h of the initial eruption a 3 km long lava flow was evident (Instituto Geográfico Nacional, 2022). The eruption lasted for more than 85 d and built a pyroclastic cone of about 225 m in height. Over the period of the eruption, the volcano showed dynamic and changing activity with new vents frequently opening on the active cone. These vents produced explosive and effusive eruptions of varying intensity (Castro and Feisel, 2022). Bulk tephra, matrix glass and glass inclusions have a basanitic–tephritic composition of 43 wt % to 46 wt %.

Since the onset of the 2021 Tajogaite eruption on 19 September, frequent measurements of SO₂ emission rates using miniDOAS traverses by car, ship and helicopter have been performed. Using these data a flux of over $5 \times 10^4 \text{ t d}^{-1}$ of SO₂ was estimated (Pérez et al., 2022). Daily monitoring of SO₂ gas emissions occurred before and throughout the eruption using TROPOMI (TROPOspheric Monitoring Instrument) data from the Sentinel-5P satellite (Copernicus SO₂ satellite monitoring; Smithsonian Institution's Global Volcanism Program, 2021). The range of measured emissions rates depended upon wind direction and velocity, as well as eruptive style and activity. The measured SO₂ flux ranged from 3×10^4 to $5 \times 10^4 \text{ t d}^{-1}$ at the beginning of the eruption and had a mean of 10^4 t d^{-1} over the duration of the active eruption (Albertos et al., 2022). These SO₂ emission rates are likely different from CO₂ but provide the best

available proxy for CO₂ emissions and are a useful point of comparison for our UAS-based flux estimates in addition to the measurements made by Burton et al. (2023) in October 2021, which range from 3.36×10^4 to $4.19 \times 10^4 \text{ t d}^{-1}$.

Additional gas monitoring techniques deployed during the eruption included stationary Multi-GAS- (multiple gas analyzer) and FTIR-based plume gas composition measurements as well as carbon isotope analyses of plume CO₂ in collaboration with the international volcanic gas community (Pérez et al., 2022).

2 Methods

Our aim was to measure plume CO₂ concentrations, calculate the resulting flux and obtain isotope data from samples taken within the plume. To achieve these goals we utilized the Dragonfly UAS, with an approximate battery life of 50 min. This extended flight time enables long-distance transects to capture large plumes. CO₂ concentrations were measured by a PP Systems SBA-5 IR sensor mounted on the Dragonfly with data transmitted to the pilot in real time (Ericksen et al., 2022). Wind velocity and direction were derived from the ERA5 model of the European Centre for Medium-Range Weather Forecasts 10 m height wind velocities corresponding to the time of each flight (Liu et al., 2020). These measurements were independently validated using a handheld anemometer and the UAS drift method (Liu et al., 2020; Galle et al., 2021). For the drift method, a Dragonfly was programmed to maintain its altitude but not its lateral position and allowed to drift with the plume. We used this estimate of wind velocity within the plume with the highest CO₂ concentration (plume B) to parameterize the flux estimation (Fig. 2).

At the location with the highest measured CO₂ concentration, a timed trigger activated a small pump and a plume gas sample was collected into a Tedlar bag (Figs. 2 and 3). We also collected gas samples of the plume from the ground when the wind direction was favorable and volcanic activity permitted. Ground-based plume samples were analyzed by infrared isotope spectroscopy with a Delta Ray located at the INVOLCAN Volcano Observatory, La Palma, following the procedure described previously (Fischer and Lopez, 2016; Ilanko et al., 2019). The error bounds on the $\delta^{13}\text{C}$ measurements are less than 0.1 ‰ for all analyses.

We also placed a Multi-GAS instrument at an accessible and safe location about 1 km to the north of the crater. Data from this instrument recorded CO₂ and SO₂ concentrations in the gas plume. The ratios were calculated using the Ratiocalc software, and we report averages for each day of the experiment.

Crosswind transects were flown downwind of the eruption to encounter the plume. CO₂ was measured at 10 Hz during flights across the plume at specified altitudes relative to launch. Each measurement was correlated to the latitude, lon-

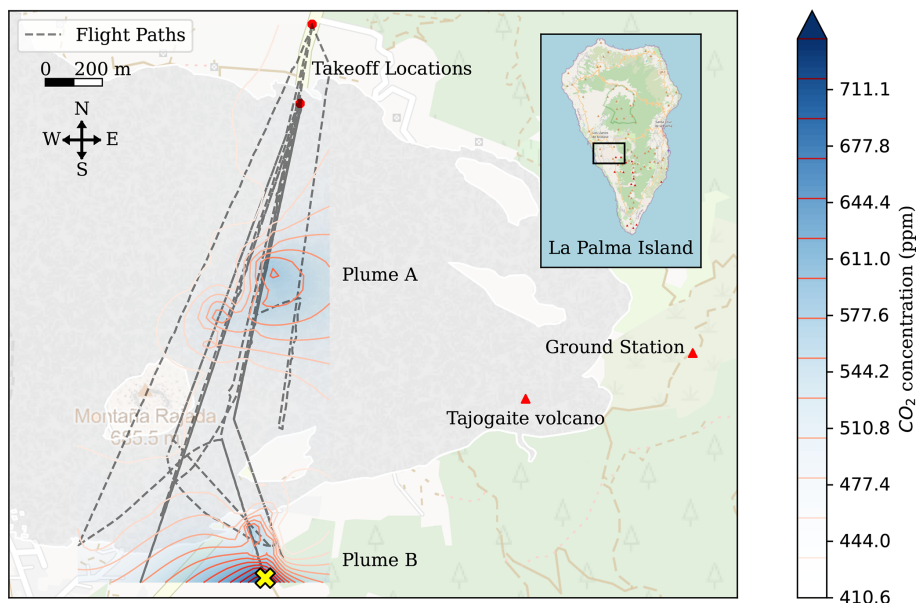


Figure 2. Top-down perspective map of all transect flight paths. Flights occurred over a 4 d period during the 2021 eruption. This map includes a horizontal cross-section Kriging plot of the CO₂ concentration highlighted as the distinct plume A and plume B. The sample collection location is indicated by the yellow \times . Insert shows the location of Tajogaite volcano on the island of La Palma. Map images © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

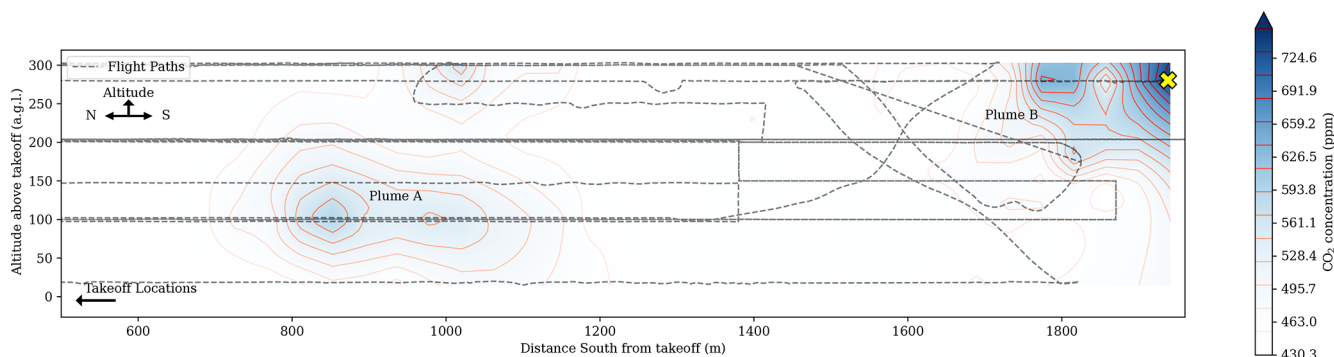


Figure 3. Lateral-perspective Kriging map of all transects plotted in Fig. 2. The plot indicates two separate plumes in the vertical cross-section labeled plume A and plume B. The sample collection location is indicated by the yellow \times .

gitude, altitude and time of the UAS during flight, giving a CO₂ concentration cross-section of the plume.

We set the ambient background CO₂ to the value observed outside the plume for each flight. The actual measurements of ambient CO₂ were made well outside of the plume (up to 400 m away from the edge of the plume) and only vary from 415 to 430 ppm.

To estimate the total flux of the plume, we perform the following procedure.

1. Convert GPS coordinates into a linear distance in meters from the launch point. Each distance is normalized to the wind direction perpendicular by multiplying it by $\cos(\text{heading}_{\text{uas}} - \text{heading}_{\text{wind}})$.

2. Isolate the plume by setting an ambient CO₂ threshold and removing data points less than that threshold.
3. Fit a Gaussian curve to the data set as follows.

- a. Calculate the mean μ and standard deviation σ of the CO₂ across the transect.
- b. Scale the 2D Gaussian curve to fit the data by choosing a constant amplitude a using the gradient descent to minimize the squared difference between the model and plume sample data. We assume that the Gaussian shape is uniform in both the x and y dimensions.

$$\begin{aligned}
 & \text{GaussianModel2D}() \\
 &= a \frac{e^{-\frac{1}{2}\left(\frac{x-\mu_x}{\sigma_x}\right)^2}}{\sigma_x \sqrt{2\pi}} \frac{e^{-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2}}{\sigma_y \sqrt{2\pi}} \\
 &= a \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma \sqrt{2\pi}} \frac{e^{-\frac{1}{2}\left(\frac{y}{\sigma}\right)^2}}{\sigma \sqrt{2\pi}} \\
 &= a \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma^2 2\pi} \\
 & y = 0, \mu_y = 0, \sigma = \sigma_x, \sigma_y = \sigma, \mu = \mu_x \quad (1)
 \end{aligned}$$

4. Integrate the 2D Gaussian and multiply by the measured wind velocity v to obtain plume flux in $\text{mg S}^{-1} \text{m}^{-2}$. Multiplying this again by the number of seconds in a day and the number of milligrams in a metric ton gives the flux in metric tons per day (t d^{-1}).

$$\int \text{GaussianModel2D}() = a \int \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma^2 2\pi} = a \quad (2)$$

$$\text{flux}(a, v) = v a \quad (3)$$

Uncertainty in the flux calculation is given by the following root sum of squares (RSS) method which combines the uncertainties in wind velocity ϵ_v , wind direction ϵ_d , sensor error ϵ_s and background CO₂ ϵ_b . The total uncertainty ϵ is calculated in accordance with the uncertainty estimation techniques described in Nassar et al. (2021), Lin et al. (2023), Nassar et al. (2017) and Johnson et al. (2020).

$$\epsilon = \sqrt{\epsilon_v^2 + \epsilon_d^2 + \epsilon_s^2 + \epsilon_b^2} \quad (4)$$

3 Results

Flux estimates are derived from the three UAS transects that crossed plume A. These transects were collected on 26 and 27 November 2021. Other transects shown in Fig. 2 either did not intersect any plume or did not cross the entire plume. In the latter case this resulted in a poor fit to the Gaussian distribution, violating our assumption of normality. We also report carbon isotopes of plume CO₂ and flux estimates based on the Multi-GAS CO₂ / SO₂ ratios.

3.1 Plume transect wind measurements

The calculated CO₂ flux for the five relevant transects with the corresponding wind velocities and directions are shown in Table 1 for transects across plume A and plume B. The wind velocity measured by UAS drift method was 10.7 m s^{-1} . ERA5 modeled wind velocities yielded results ranging from 10.0 to 12.2 m s^{-1} with an average of 11.1 m s^{-1} . The wind direction given by the ERA5 model yielded results ranging from 38 to 68° , with an average of 53° . These ranges contribute to the overall uncertainty ϵ_d .

3.2 Carbon isotopes of plume CO₂

The CO₂ concentrations and $\delta^{13}\text{C}$ values of plume gas samples are given in Table 2. Samples collected from the ground at the University of New Mexico (UNM) Multi-GAS site show background CO₂ concentrations of 416 to 471 ppm CO₂ with $\delta^{13}\text{C}$ values of -8‰ (relative to Vienna Pee Dee belemnite, VPDB), which is close to that of air. The sample collected by UAS has a CO₂ concentration distinctly elevated from air of 671 ppm and a heavier $\delta^{13}\text{C}$ value of -4.44‰ .

Samples collected from the ground closer to the vent have even higher CO₂ concentrations from 1030 to 4459 ppm with $\delta^{13}\text{C}$ values from -2.40‰ to -1.47‰ .

3.3 Multi-GAS measurements of plume

The Multi-GAS CO₂ / SO₂ ratios during the period from 21 to 25 November 2021 range from 5 to 26 and are shown in Table 2. These values are consistent with those reported by Albertos et al. (2022) and Burton et al. (2023). We use the range of reported SO₂ fluxes (mean of 10^4 t d^{-1} over the duration of the active eruption; Albertos et al., 2022) in combination with the range of our Multi-GAS CO₂ / SO₂ ratios to obtain CO₂ fluxes ranging from 7.3×10^4 to $3.6 \times 10^5 \text{ t CO}_2 \text{ d}^{-1}$ for this period (Table 3).

4 Discussion

This work highlights our efforts in collecting and analyzing CO₂ gases during the Tajogaite volcanic eruption. Through this work, we demonstrated the efficacy of using a UAS to study the CO₂ plumes associated with an in-process eruption.

4.1 CO₂ emissions

Our UAS-based CO₂ emission estimation technique yields CO₂ fluxes using direct measurement with a single instrument type. This simplifies the estimation of CO₂ flux. However, in situ measurement during an active eruption is challenging. The most serious difficulty we encountered was obtaining complete transects across the plume or plumes. In several of our transects, especially for the more distant plume B, we were not successful in flying the UAS far enough to get to background CO₂ on the far side of the plume. Gas plumes change shape and direction on relatively short timescales as the wind shifts. While, ideally, we would like to perform several flights at various altitudes through a plume in order to obtain a complete CO₂ concentration map of the plume, this is challenging for wide or distant plumes because of limited UAS flight times and the need to know the plume's location and extent a priori. To address this challenge we assume a Gaussian plume and fit a Gaussian curve to our data. We then rotate the Gaussian fit to obtain a 2D concentration slice which is multiplied with estimated wind velocity to yield the flux. This approach produces the most

Table 1. CO₂ data collected by UAS across plume A and plume B during the Tajogaite eruption.

Date (yyyy-mm-dd)	Transect	Altitude	Wind (m s ⁻¹ at °)	Max concentration (ppm)	Gaussian fit amplitude	R ²	Flux (t d ⁻¹)
2021-11-26	2 (plume A)	200 m	11.8 at 68°	501	8.95 × 10 ⁵	0.93	1.76 ± 0.20 × 10 ³
2021-11-27	6 (plume A)	100 m	12.2 at 38°	616	1.10 × 10 ⁷	0.71	2.23 ± 0.26 × 10 ⁴
2021-11-27	7 (plume B) ^b	100 to 250 m	12.2 at 38°	613	3.02 × 10 ⁶	0.01	6.15 ± 0.71 × 10 ³
2021-11-27	8 (plume A)	300 m	12.2 at 38°	577	2.81 × 10 ⁶	0.75	5.71 ± 0.66 × 10 ³
2021-11-28	9 (plume B) ^{a,b}	300 m	11.3 at 44°	963	3.85 × 10 ⁷	0.36	7.25 ± 0.84 × 10 ⁴

^a Transect with samples collected into Tedlar bags and analyzed by infrared isotope ratio spectroscopy. ^b Transects that encountered plume B but for which the gas distribution did not meet our Gaussian fit assumptions, as indicated by the low R² value in comparison to the Gaussian amplitude. Thus we did not include plume B in our flux calculations.

Table 2. Measured CO₂ concentrations and δ¹³C from the ground and UAS.

Date (yyyy-mm-dd)	CO ₂ (ppm)	δ ¹³ C (VPDB ‰)	Collection method/site
2021-11-21	435	-7.46	Ground
2021-11-21	472	-8.34	Ground
2021-11-21	437	-7.65	Ground
2021-11-21	416	-8.00	Ground
2021-11-28	671	-4.44	UAS
2021-11-30	1030	-3.65	Ground
2021-11-30	2998	-2.12	Ground
2021-11-30	2863	-2.15	Ground
2021-12-01	4459	-2.03	Ground
2021-12-01	2722	-1.47	Ground
2021-12-01	1326	-2.40	Ground

Table 3. Multi-GAS measurements, SO₂ flux and computed CO₂ flux.

Date (yyyy-mm-dd)	Average CO ₂ / SO ₂ (molar)	SO ₂ flux (t d ⁻¹)	CO ₂ (t d ⁻¹)
2021-11-21	26 ± 15	2 ± 1 × 10 ⁴	3.6 ± 1.8 × 10 ⁵
2021-11-22	10 ± 2	2 ± 1 × 10 ⁴	1.4 ± 0.7 × 10 ⁵
2021-11-23	5 ± 2	2 ± 1 × 10 ⁴	7.3 ± 3.7 × 10 ⁴
2021-11-24	7 ± 2	2 ± 1 × 10 ⁴	9.5 ± 4.8 × 10 ⁴
2021-11-25	16 ± 2	2 ± 1 × 10 ⁴	2.3 ± 1.1 × 10 ⁵

accurate results if we transect the plume through its widest part. However, identifying the widest part and then transecting the plume before the plume changes will require teams of collaborating UASs. A good fit of the data by the Gaussian model is given by a high R² value. For instance, transect 2 was fit with a R² value of 0.93 and accounts for 93 % of the variance in the observed data. The model fit represented by this high R² value is depicted in Fig. 4.

Uncertainty is introduced by the assumptions made by the model. We combine the various sources of uncertainty using

the RSS method (Eq. 4). With just one horizontal transect, we assume the vertical Gaussian standard deviation is identical to the horizontal standard deviation of the plume. The standard deviations of both dimensions are linearly correlated to the flux calculation, meaning that a 20 % error in the vertical standard deviation will affect the flux estimate by 20 %. We estimate that the vertical standard deviation is likely close to the horizontal standard deviation, but the difference is impossible to determine. Additionally, we assume that the horizontal transect samples the plume at the altitude where the plume is widest. If the transect is not through the largest cross-section, the flux calculation may be a lower bound. Wind velocity was measured during one of the transects, but weather is notoriously unpredictable. This represents another source of uncertainty in the model which has a linear effect on the flux measurement. We used our wind estimates during the time of each flux calculation. This variation in wind velocity ϵ_v is ±11 %, which is calculated from the wind velocity range measured over the experiments (Table 1). The range of wind directions is ±15° from Table 1, which gives an error in the flux estimate based on $\epsilon_d = 1 - \cos(\text{angle})$, thus ±3.40 %. The SBA-5 documentation reports sensor error ϵ_s of 1 % in the range of CO₂ we measured. Finally, background ambient CO₂ ϵ_b adds 1 % to the uncertainty model which we calculated from the uncertainty in ambient CO₂ readings. Therefore, our estimated flux uncertainty given by the RSS method is $\epsilon = \pm 11.61$ %.

Our data show that for plume A, transect 6 (Fig. 3) represents the widest plume and results in the highest CO₂ flux value of 2.23 ± 0.26 × 10⁴ t d⁻¹, an order of magnitude higher than the other two plume A transects. This transect was flown at the lowest altitude (100 m) of the three, implying that the other two transects only captured the upper parts of the plume. Comparison with CO₂ fluxes obtained by combining SO₂ fluxes with CO₂ / SO₂ ratios measured 1 km from the vent gives fluxes ranging from 7.3 × 10⁴ to 3.6 × 10⁵ t CO₂ d⁻¹ (Table 3). Therefore our highest flux measurement is consistent with the lowest estimate using the combined method. While comparing these two approaches is helpful, our experiment was not designed to make a di-

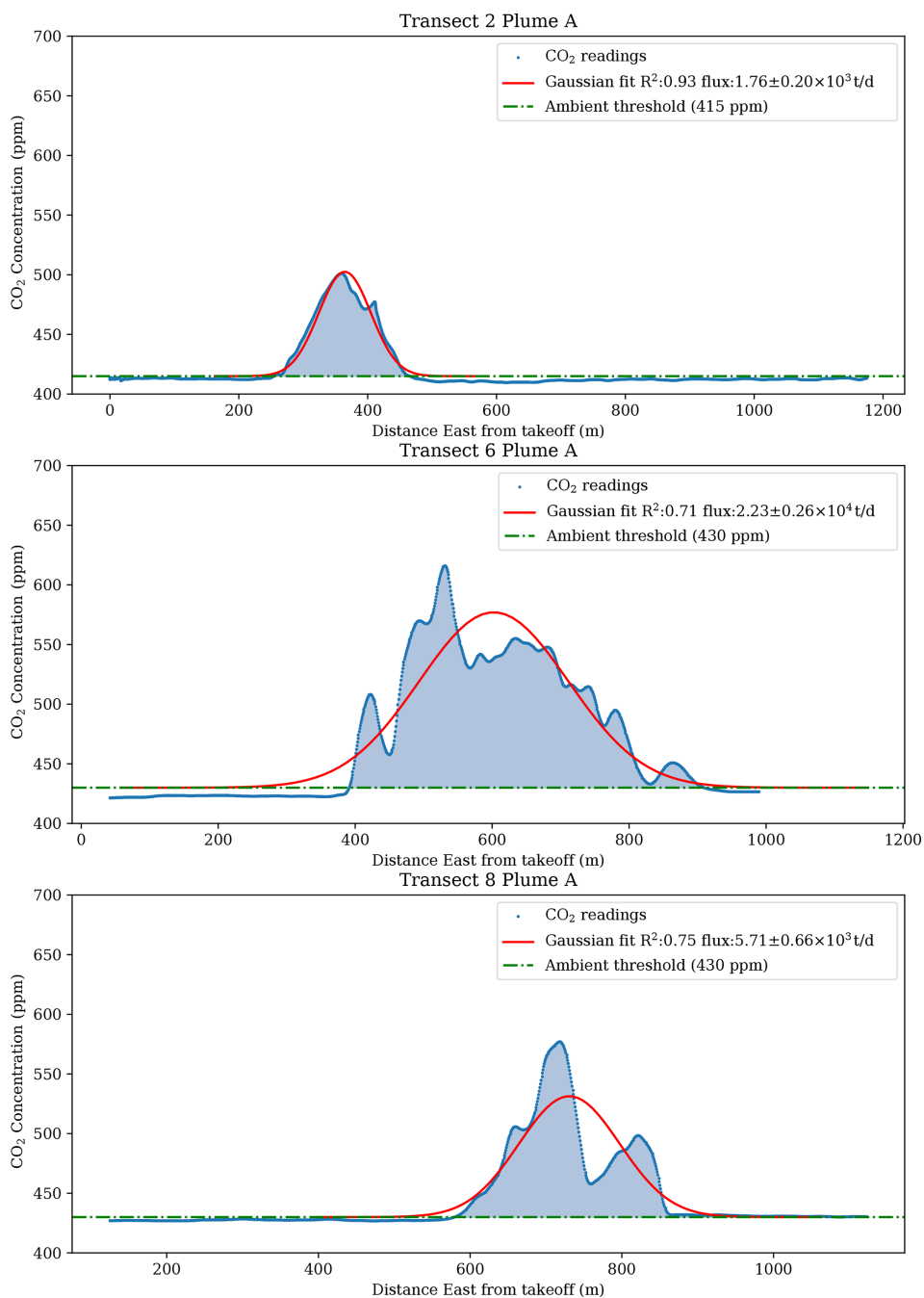


Figure 4. Three plots of encounters with plume A with the closest Gaussian model fit. CO₂ concentration (blue) over the encountered plume as a function of distance from the takeoff location.

rect comparison. The discrepancy could be due to a significantly varying CO₂ emission rate during eruptions, an overestimate of the SO₂ flux or the lack of validity of the 2D Gaussian extrapolation approach. Our estimates are consistent with the October 2021 high emissions presented by Burton et al. (2023), who report fluxes of 3.36×10^4 to 4.19×10^4 t CO₂ d⁻¹ (389 to 486 kg s⁻¹) for the smaller, non-ashy plume that we measured. More work needs to be performed

in the future to better assess sources of discrepancies with new and coordinated measurements at passively degassing and erupting volcanoes. However, even with such discrepancies, it is clear that the Tajogaite eruption in November 2021 produced a CO₂ flux up to 2×10^4 t d⁻¹ or even 5×10^5 t d⁻¹. Even the 5×10^5 t d⁻¹ would be only 0.4 % of the daily CO₂ emitted by the burning of fossil fuels (Conlen, 2021).

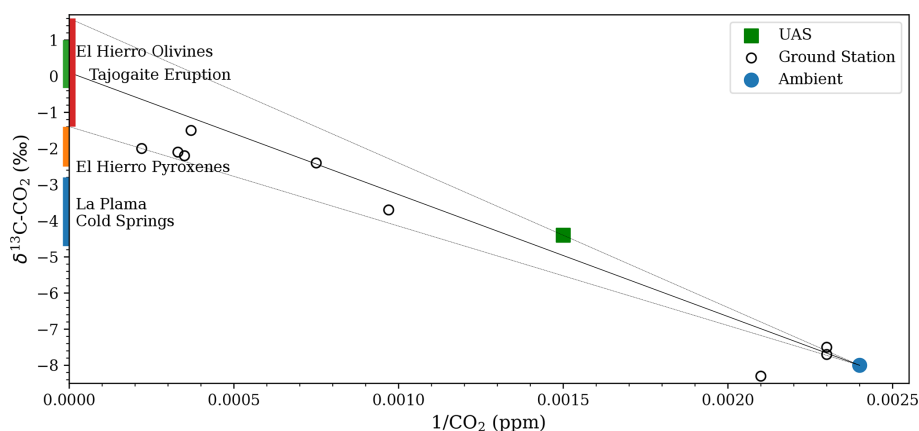


Figure 5. Keeling plot showing standard air and samples collected on the ground, as well as with the UAS. Linear extrapolation indicates a volcanic $\delta^{13}\text{C}\text{-CO}_2$ value of -1.40‰ to 1.60‰ . Also shown are data from olivines and pyroxenes collected at El Hierro volcano (Sandoval-Velasquez et al., 2021) and the composition of cold CO₂-rich gas discharges on the island of La Palma (Padrón et al., 2015).

4.2 Carbon isotopes

The carbon isotope data obtained from the UAS-captured samples and the samples collected from the ground are generally consistent and show mixing of air-derived CO₂ with a deep magmatic source. Figure 5 shows that all plume samples collected from the ground define a set of mixing lines in $\delta^{13}\text{C}\text{-CO}_2^{-1}$ space, i.e., in a Keeling plot (Keeling, 1958) that allows for the extrapolation of the $\delta^{13}\text{C}$ value of the pure CO₂ being emitted from the volcanic vent. The sample collected by UAV lies slightly above this set of mixing lines and extrapolates to somewhat heavier $\delta^{13}\text{C}$. The resulting volcanic $\delta^{13}\text{C}$ values taking into account all samples lies between -1.5‰ and $+1.5\text{‰}$. Despite these uncertainties, these values overlap with $\delta^{13}\text{C}$ data obtained from mantle xenoliths in lava erupted at the nearby El Hierro volcano (Sandoval-Velasquez et al., 2021).

Extrapolation of all these data results in a $\delta^{13}\text{C}$ value of $0.1 \pm 1.5\text{‰}$. Notably the carbon isotope values are significantly heavier than those measured in cold CO₂-rich gas discharges from springs on La Palma (Padrón et al., 2015) and within the range of values measured in olivines and pyroxenes of xenoliths from the island of El Hierro (Sandoval-Velasquez et al., 2021). These authors suggested that the heavy values of the xenoliths are related to recycling of crustal carbon, likely derived from carbonates into the mantle source of the Canary Islands hot spot. Our data suggest that the magmatic system that is driving the Tajogaite eruption taps into this deep CO₂, rather than remobilizing CO₂ that feeds the cold degassing springs on the island. Sandoval-Velasquez et al. (2024) report $\delta^{13}\text{C}$ values measured in olivines, clinopyroxenes and orthopyroxenes from lava flows erupted in 2021. Their data are consistent with our extrapolated heavy $\delta^{13}\text{C}$ values. For olivines, representing the earliest crystallization phase, their values range from 0‰ to 1‰ . Values are somewhat lighter for orthopyroxenes

and clinopyroxenes. Using all data, their estimated mantle endmember is -1.5‰ . Our data extrapolate to -1.4‰ to $+1.6\text{‰}$. Given the difference in sample medium, i.e., phenocrysts versus gas plume, the results are remarkably consistent. More work on erupting volcanoes is needed to better constrain the sources of magmatic CO₂ emitted during heightened activity of volcanic systems.

5 Conclusion

The use of UASs is revolutionizing volcano science by enabling the collection of data that previously required extensive, costly and hazardous aerial surveys using piloted fixed-wing aircraft or helicopters. Especially in the field of volcanic gases, recent UAS-based campaigns showed the value of utilizing UASs to make gas flux and gas composition measurements and also collect plume samples for subsequent chemical and isotopic analyses (Liu et al., 2020; Galle et al., 2021). Our work during the explosive and hazardous eruption of Tajogaite volcano shows that CO₂ emission measurements and plume gas samples can be collected even during these heightened periods of volcanic activity. We demonstrate that a UAS capable of automated sampling can be guided by the expert knowledge of scientists in the field to collect valuable data that would be impossible with robots or scientists alone. The collected data provide key insights into the volcano's state and the course of an eruption. Future work is needed to increase UAS autonomy in choosing flight paths to more completely capture data from dynamic plumes, but, as we have demonstrated, the present approach works for volcano monitoring during eruptions and can provide much-needed information about eruptive gas emissions.

Appendix A

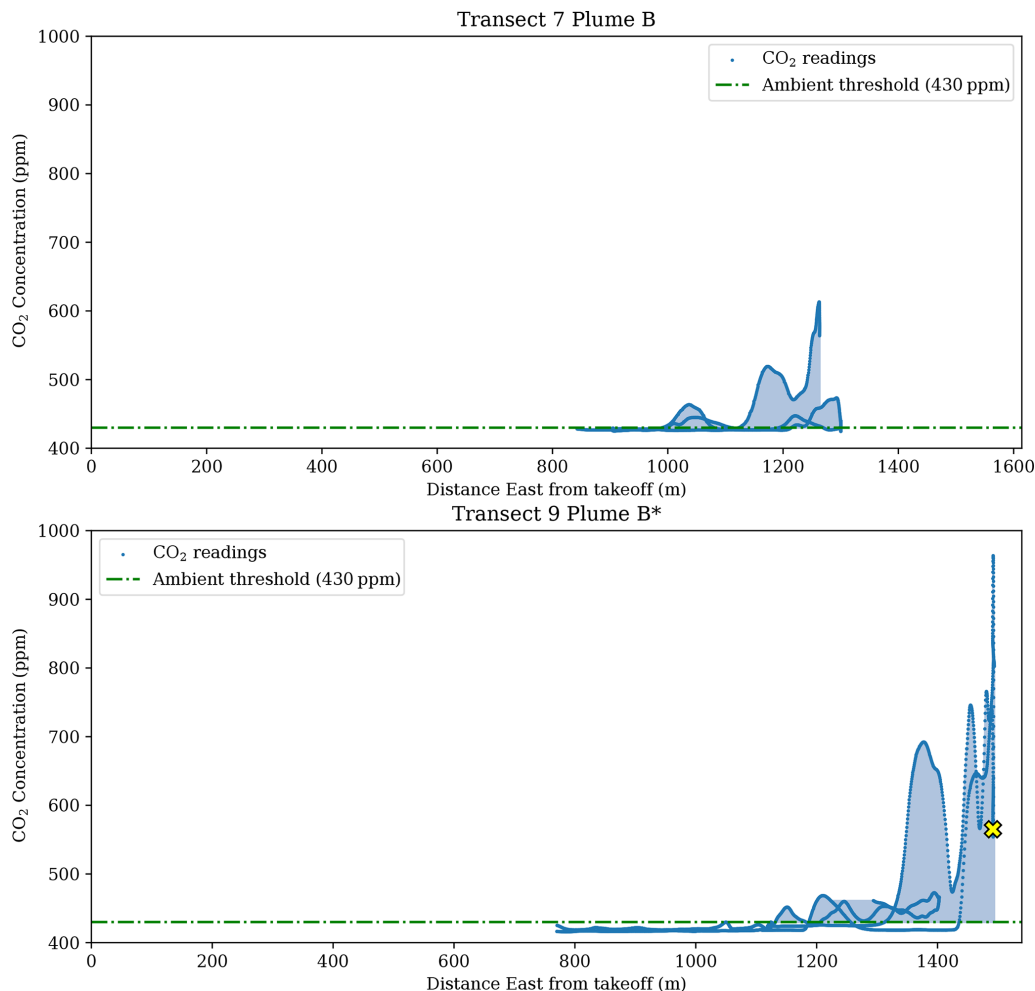


Figure A1. Encounters with plume B were not as well fit as plume A encounters. These plots show the CO₂ readings collected during the two highest plume model fits. As with Fig. 4, CO₂ concentration (blue) over the encountered plume as a function of distance from the takeoff location. The sample collection location is indicated by the yellow ×.

Code and data availability. All data needed to evaluate the conclusions in the paper are present in the paper. Additional data and plot generation code are available at https://github.com/BCLab-UNM/lapalma-expedition/tree/2021_tajogaite_eruption (last access: 8 August 2024; <https://doi.org/10.5281/zenodo.13274766>, Ericksen and Fricke, 2024). UAS code is available at <https://github.com/BCLab-UNM/dragonfly-dashboard> (last access: 8 August 2024; <https://doi.org/10.5281/zenodo.13274798>, Ericksen and Frost, 2024) and <https://github.com/BCLab-UNM/dragonfly-controller> (last access: 8 August 2024; <https://doi.org/10.5281/zenodo.13274812>, Ericksen et al., 2024).

Author contributions. JE, GMF, SN and TPF (UNM VolCAN team) performed UAS fieldwork for this paper. JE, NMP, PHP, EPG (INVOLCAN team) and TPF conducted the ground fieldwork. JE developed UAS software and hardware and was supervised by GMF and MEM. SN designed the sample collection device. JE, NMP, PHP and EPG performed data analysis. TPF performed isotope and gas analysis. JE, TPF, GMF, SN and MEM wrote the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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