1. Introduction

The measurement of volcanic fluxes in plumes has largely focused on SO$_2$ because of its low ambient concentrations and strong UV absorbent, which makes it an ideal volcanic tracer (McGonigle et al., 2017). The optical density of each pixel in a volcanic gas plume, as measured by a UV-camera, is proportional to the column amount of SO$_2$ in the plume (Kern et al., 2013; McGonigle et al., 2017). The integrated column amount, also known as ICA, of SO$_2$ is multiplied by the wind speed to estimate the SO$_2$ flux. The ICA of SO$_2$ typically varies in time (Ilanko et al., 2020; McGonigle et al., 2005); understanding the origin of these fluctuations is of great interest for interpreting volcanic gas emission regimes. However, volcanic gas plumes are highly turbulent, with speeds, $u$, of the order 1–10 m s$^{-1}$, lateral scale, $L$, of 100's m leading to Reynolds numbers of $10^7$–$10^8$ where

$$Re = \frac{uL}{\nu}$$  \hspace{1cm} (1)

where $\nu$ is the dynamic viscosity of the air (Sparks, 1997). This leads to turbulent fluctuations in the plume speed and concentration (Wang & Law, 2002) which can also affect the ICA of SO$_2$, and we explore this herein.

Spectroscopic data sets from a number of volcanoes (Figure 1) show both high- and low-frequency fluctuations. For example, at Bromo Volcano (Aiuppa et al., 2015), Mount Etna (Boichu et al., 2010), Gorely Volcano (Aiuppa et al., 2012), Mount Etna (Tamburello et al., 2013), Stromboli Volcano (Tamburello et al., 2012), Masaya Volcano (Pering, Ilanko, Wilkes, et al., 2019), Sabancaya Volcano (Ilanko et al., 2019), Villarrica Volcano (Liu et al., 2019), Villarrica Volcano (Liu et al., 2019), and Yasur Volcano (Ilanko et al., 2019; Woitischek et al., 2020). Spectroscopic data are typically collected from a single location, thereby providing a time series of the fluctuations in the signal which may be associated with both the turbulence at that location, as well as any intermittency in the source gas flux. In Figure 1, we see a wide range of fluctuations that range from low- to high-frequencies as well as showing a variety of amplitudes. In Figure 1a, the fluctuations at Mount Etna are rather continuous while at Stromboli Volcano, we observe short-period fluctuations every $70 \pm 10$ s (Figure 1b, red circles) and longer period fluctuations every $500 \pm 100$ s (Figure 1b, yellow circles). At Villarrica Volcano, we observe long-period fluctuations of about $140$ s (Figure 1c, yellow circle) and shorter period fluctuations of $100 \pm 40$ s (Figure 1c, red circles). At Yasur Volcano, we see long-period fluctuations (Figure 1d, yellow circle) with periods of $100 \pm 10$ s and shorter period fluctuations every $10–20$ s (Figure 1d, red circles).

---

**Key Points:**

- If the frequency of the source is comparable to the frequency of the turbulence associated with the plume, it is difficult to distinguish specific explosions.
- If the frequency of the source is lower than the frequency of the turbulent fluctuations in the plume, discrete puffs form.
- The frequency of turbulent fluctuations in a plume decrease with distance downstream.

**Abstract**

Some basaltic open vent volcanoes show that spectroscopic SO$_2$ measurements of a volcanic gas plume are characterized by a fluctuating signal. Understanding the origin of these fluctuations is of great interest for interpreting volcanic gas emission regimes. Although some fluctuations may be associated with intermittency in the source flux, some may be associated with the turbulence in the flow. A simple laboratory experiment, in which we release dye pulses into a turbulent wake in a small water-filled channel, suggests that when the intermittency of the source has comparable or smaller timescale as the turbulence, the fluctuations are similar, whereas when the intermittency of the source has longer timescale than the turbulence, the fluctuations can be distinguished. We also present some small-scale laboratory experiments of turbulent buoyant plumes produced from a steady source; these demonstrate a time-fluctuating concentration of source fluid downstream and the fluctuation period tends to increase with distance.
If the gas source is associated with very high frequency bubble bursting at the volcanic vent, with frequency larger than that of the plume turbulence, then we expect that gas from successive release events may be mixed together by the turbulence, and the signal may be difficult to distinguish from a more continuous source of gas (e.g., Etna, Figure 1a). In contrast, if the source of gas has a very long period between explosions compared to that of the turbulence, then we expect that discrete clouds of gas may be identified as they move downstream (e.g., Yasur, Figure 1d). In Section 2, we present a laboratory experiment to illustrate how tracer released from an intermittent source becomes mixed as it moves downstream in a turbulent wake flow; we focus on the difference in the tracer pattern as the relative frequency of the source and the turbulence change. We then present data illustrating how the concentration of a tracer released from a steady source varies with distance downstream in a laboratory model of a turbulent buoyant plume or wind-driven buoyant plume, owing to the evolution of the turbulence in the flow. We draw some conclusions about distinguishing intermittency in source conditions with the plume turbulence in integrated column data collected from volcanic gas plumes.

2. An Idealized Turbulent Flow Experiment

To illustrate how turbulence in a well-characterized turbulent flow overprints the signal from an intermittent source of tracer, we have carried out a simple series of experiments in which a tracer is added intermittently to a turbulent wake flow (Figure 2, Cafiero and Woods, 2016). The turbulent flow is produced in a small water-filled flume, of size 15 × 100 × 1 cm, as an initially uniform flow passes a cylindrical obstacle (Figure 2a). We then release an intermittent source of dye into the wake flow just behind the cylinder, using a Watson Marlow 520 N peristaltic pump, and we record the flow downstream.

Figure 1. Fluctuations in spectroscopic gas measurements. (a) Etna (Tamburello et al., 2013), (b) Stromboli (Tamburello et al., 2012), (c) Villarrica (Liu et al., 2019), and (d) Yasur (Ilanko et al., 2020). Red circles indicate high-frequency and low-amplitude fluctuations whereas yellow circles point out high-amplitude and low-frequency fluctuations (b–d). In contrast, Etna shows a rather constant signal in frequency and amplitude.
In this experiment, the volume flux through the cross-section of the tank varies between 0.2 and 0.5 liters per second. The Reynolds number of this flow is of the order 10^3 as given by Equation 1 where \( u \) is the flow speed, \( L \) is the thickness of the tank (0.01 m), \( \rho \) is the density of water (997 kg m\(^{-3}\)), and \( \mu \) is the dynamic viscosity of water (10^{-3} kg m\(^{-1}\) s\(^{-3}\)). The turbulent wake which results when the flow passes the obstacle leads to a very regular stream of eddies with frequency between 1.9 and 4.5 Hz (Figure 2b, panel i). With no obstacle, there is no wake, and dye pulses move downstream with the uniform flow (Figure 2b, panel ii).

In Figure 3, we show the results of four experiments in which there was intermittent release of dye into the wake just downstream of the cylinder. Figure 3a illustrates the light intensity seen along a line normal to the direction of the flow, 30 cm downstream of the source, as a function of time and Figure 3b shows the light intensity averaged along this line of pixels as a function of time. The dye was released with four different frequencies: 0.2 (panel i), 3.0 (panel ii) and 6.0 Hz (panel iii), and a continuous source (panel iv). In these experiments, the wake frequency was 3.6 Hz in panel (i) and 2.5 Hz in panels (ii and iii) and 4.5 Hz in panel (iv). With a dye release frequency of 0.2 Hz (panel i), the pulses of dye have much longer period than the turbulence, and each pulse spans several of the eddies in the wake (panel i). In contrast for a dye release frequency of 3.0 and 6.0 Hz (panels ii and iii), the pulses of dye have a similar or higher frequency to those of the eddies, and it is difficult to distinguish whether the fluctuations in the dye intensity arise from the turbulence or the source. In panel (iv), there is a continuous source of dye, and this is similar to panel (iii).

In order to explore the time series further, we have applied a continuous wavelet transform (with the Morlet as a mother wavelet) to the data (Figure 3c), as is often used in analyzing spectroscopic signals in volcanic gas plumes (Liu et al., 2019; Pering, Ilanko, & Liu 2019). The continuous wavelet transform scalograms distinguish the high and low frequency in panel (i) and, to some extent, in panel (ii), but as the two frequencies converge, the signal is more complex. This simple experiment illustrates that with a well-characterized turbulent wake, fluctuations in the dye concentration in the wake arising from the turbulent mixing can be distinguished from fluctuations associated from the intermittency in the source provided the frequency of the intermittent source is significantly smaller that of the wake. However, as the frequencies converge, the eddies mix and disperse the dye nonlinearly leading to a highly convolved signal.
3. The Impact of the Buoyancy of the Gas

In a real volcanic gas plume (Figures 4a and 5a), the combination of high temperature and the buoyancy of water vapor relative to air leads to the formation of a buoyant plume of gas, which may either rise above the volcano or eventually be swept downwind as it rises. In such buoyancy-driven plumes, the turbulence evolves with distance downstream, unlike the illustrative wake flow experiments shown in Section 2. We now present some further experiments (Figures 4f and 4g) which illustrate how, even with a constant source flux, the turbulence in such plumes can lead to intermittency in the gas content as measured at a given point.

3.1. Vertical Plumes

We analyzed the intermittency in a small-scale turbulent buoyant plume produced in a laboratory tank (Figure 4f). The tank was initially filled with fresh water and we used a source of saline solution with a concentration of 5 wt% NaCl (a density of 1,056 kg m\(^{-3}\)) supplied to a point source at the top of the tank with a flux 11 cm\(^3\) s\(^{-1}\). Again the saline solution was supplied by a Watson Marlow 520 N peristaltic pump. We note that the frequency of the pulses from this pump was 5 Hz which is much higher than any of the fluctuations seen in the experiments and, hence, in these experiments, the source is effectively continuous. The plume was dyed red to enable visualization of the flow. A movie of the plume was recorded using a Nikon D900 camera with a frame rate of 30 fps.

In Figure 4b, panels i–iii, we illustrate three time series of light intensity averaged across three horizontal planes which cut through the turbulent buoyant laboratory plume (Figure 4a). The image illustrates that
**Figure 4.** (a) Photograph of the laboratory plume and (b) variations of the light intensity in the experimental plume as a function of time at three heights in the plume (5, 16, and 29 cm). (c) Photograph of the Villarrica plume and (d) an illustration of the variation with time of the light intensity measured at three height in the plume (100, 390, and 670 m). (e) Time series of images showing distinct eddy type features of Villarrica's vertical plume. Images are taken at 20 s intervals. We have highlighted the ascent and merging of eddies. Schematic illustration of the set-up of the (f) vertical plume experiment and (g) the wind-blown plume experiment.
there are considerable fluctuations in the signal in time, and that the average frequency of the turbulent fluctuations in the plume appears to decrease with distance from the source. Wang and Law (2002) and Papanicolau and List (1988) have studied the evolution of the mean and turbulent properties of vertical plumes. Classical plume theory predicts that the mean speed of the flow, \( U \), and hence of the eddies, decreases with height according to the idealized model

\[
U = \beta v B z^{-\frac{1}{3}}
\]

(2)

where \( \beta \sim 3.0 \) is a constant, \( B \) is the buoyancy flux, and \( z \) is the height above the source. These models suggest that the size of the eddies grows linearly with distance from the source (Morton et al., 1956). Although in any specific realization of the flow the fluctuations are highly turbulent and irregular, as seen in the video data, on average, the eddy speed decreases with height, leading to a gradual reduction in their frequency (Figure 4). Dracos et al. (1992), Jirka (2001), and Landel et al. (2012) have reported a gradual decrease in frequency of turbulent eddies with distance from the source in a two-dimensional turbulent buoyant plume.

Figure 5. (a) Photograph of the laboratory plume and (b) variations of the vertically averaged light intensity in the experimental plume as a function of time at three lines away from the source (20, 40, and 70 cm). (c) UV-photograph of the Etna NEC plume and (d) an illustration of the turbulent fluctuation with time of the light intensity measured in the plume away from the vent (20, 100 and 160 m).
In Figure 4d, panels i–iii, we present data showing the variation of the light intensity integrated from three horizontal lines of pixels recorded at three heights in the video of the gas plume at Villarrica Volcano which was recorded in the visible range of light (Figure 4c; Hicks et al., 2012). These three time series again show considerable variation in time and also variation in space which suggests that, at least in part, the fluctuations are associated with the mixing produced by an evolving field of turbulent eddies rather than purely being associated with intermittency of the source flux.

The decrease in speed and increase in size of the eddies in a turbulent plume sometimes involves the merger of eddies. Such merging processes are apparent in the Villarrica plume, as illustrated in Figure 4e. However, it is key to note that we have no independent evidence as to whether the fluctuations in this volcanic plume arise from the intermittency of the source or are associated with the turbulent fluctuations of the plume itself.

3.2. Wind-Blown Plume

The wind can lead to a wind-blown buoyant plume. To assess the nature of turbulent fluctuations which may develop even from a constant source, we present data from an analog laboratory experiment (Figures 4g and 5a). The experiment was produced in a small-scale laboratory where a continuous source of a fluid (3.5 wt% NaCl) with a density of 1,038 kg m\(^{-3}\) and volume flux 4 cm\(^3\) s\(^{-1}\) is moved at a constant speed of 0.04 m s\(^{-1}\) just below the upper surface of the fresh water. The experiment was recorded using a Nikon D900 camera, with a frame rate 60 fps.

In Figure 5b, panels i–iii, we illustrate the average light intensity as calculated along three vertical lines across a typical wind-blown laboratory plume at distances 20, 40, and 70 cm from the source. The image illustrates that there are considerable fluctuations in the integrated light intensity, and that these fluctuations vary with distance from the source, even though the plume is produced from an effectively continuous supply of fluid.

Figure 5c, panels i–iii, shows the variation of the light intensity integrated along three vertical lines through the gas plume at Mount Etna as recorded from the Pyplis example video 1: SO2 emissions test data set, 2017 (Figure 5c). The lines are located at distances of 20, 100, and 160 m downwind from the vent. Although again we do not know if the fluctuations in the Etnean plume arise from intermittency of the source or the turbulence of the flow, the laboratory experiment suggests that very significant fluctuations may arise even with a continuous source of fluid.

In both the laboratory and volcanic plume, the time series suggest that there is a decrease in the frequency of the fluctuations with distance downwind from the source. As the flow moves downwind, the plume fluid typically moves with the wind speed, \(w\), while slowly rising in the vertical direction because of the buoyancy force (Hewett et al., 1971). If the source buoyancy flux in a continuous plume is \(B\), then the buoyancy flux per unit distance downwind is \(B/w\) (Morton et al., 1956; Sparks et al., 1997). From dimensional arguments, the ascent speed of the cloud is then expected to follow the relation:

\[
U \sim \beta_h \left( \frac{B}{w} \right)^{1/2} z^{-1/2}
\]

where \(\beta_h\) is an empirical constant and \(z\) the height. The frequency decrease of the fluctuations with source distance is consistent with the theoretical prediction of a decrease in speed and increase in size of the plume as it entrains and mixes with ambient fluid, and this may lead to intermittent eddy merging in the flow.

4. Discussion

Spectroscopic gas measurements are often characterized by complex time-dependent fluctuations, which may be characterized by two distinct frequencies (Yasur Volcano, Figure 1d) or a more continuous fluctuation (Mount Etna, Figure 1a). An illustrative wake flow experiment indicated that if the source of gas has a very high frequency compared to the frequency of the turbulence, then the flow will effectively mix the
individual gas pulses, and it may be difficult to distinguish specific explosions from the data. In contrast, if the fluctuations of source of gas have low frequency compared to that of the turbulence, then the gas may form discrete puffs which move downstream. Furthermore, data from analog experiments of turbulent buoyant plumes suggest that even with a continuous source of fluid, there may be considerable fluctuations in the integrated light intensity signal with distance downstream associated with the highly turbulent character of such flows.

In analyzing the time variation of the concentration of SO$_2$ in a gas plume, it may therefore be difficult to readily distinguish fluctuations in the source flux from the fluctuations associated with the turbulence in the flow. However, data have shown that the gas composition varies with the gas flux in many basaltic eruptions. For example, at Erebus, Yasur, and Stromboli Volcano, there are periods of passive degassing between the larger discrete explosions; the two styles of degassing have volcanogenic origin and are not caused by atmospheric processes and are characterized by gas of different composition (Aiuppa et al., 2010; Bani et al., 2013; Burton et al., 2007; Oppenheimer et al., 2006, 2011; Woitischek et al., 2020). Another example in which there are changes in the gas chemistry with the eruption style at Kilauea Volcano (Edmonds & Gerlach, 2007).

We propose that if the time dependence of the plume composition is measured at a given point, this may help in distinguishing between fluctuations associated with source intermittency compared to intermittency associated with the turbulence. However, in interpreting such data, we might also need to account for the reactions within the gas plumes (Delmelle et al., 2018). Indeed, downwind there is typically a gradual decrease of SO$_2$ in the plume as it transforms into particulate sulfuric acid: measurements of this effect were reported at Soufriere Hills (Oppenheimer et al., 1998), Masaya Volcano (Nadeau & Williams-Jones, 2009), Kilauea Volcano (Kroll et al., 2015), Mount Etna (Bobrowski et al., 2007), and Villarrica Volcano (Bobrowski et al., 2007). These oxidation processes take either place on surfaces of liquid coated ash particles or aerosols or in a gas or aqueous phase if oxidants are available, for example, OH and H$_2$O$_2$ (Kroll et al., 2015; McGonigle et al., 2004; Oppenheimer et al., 1998). Other factors that might influence the the SO$_2$ lifetime in the plume close to the vent include the ambient humidity and wind speed, with the SO$_2$ typically evolving within minutes to hours of eruption (Kroll et al., 2015; McGonigle et al., 2004; Nadeau & Williams-Jones, 2009; Oppenheimer et al., 1998; Von Glasow, 2010). Other volcanic volatiles like HCl and HF may also be gradually removed from the plume through condensation (Tabazadeh & Turco, 1993).

In summary, temporal and spatial data on fluctuations in the gas composition in volcanic gas plumes may lead to new understanding of the source conditions, and of the turbulence, in such flows.

Data Availability Statement

Data are available in Tamburello et al., 2012, 2013, Liu et al., 2019, and Ilanko et al., 2020.

Acknowledgments

The authors thank Tehnuka Ilanko, Nial Peter, Yves Moussallam, Kayla Iacovino, and Kelby Hicks for providing the Villarrica plume video. The authors also thank Nicola Mingotti for providing us with the vertical and wind-blown analog experiment videos. This work was supported by the Natural Environment Research Council (grant number NE/L002507/1).

References

Aiuppa, A., Bani, P., Moussallam, Y., Di Napoli, R., Allard, P., Gunawan, H., et al. (2015). First determination of magma-derived gas emission from Bromo volcano, eastern Java (Indonesia). Journal of Volcanology and Geothermal Research, 304, 206–213.

Aiuppa, A., Bertagnini, A., Metrich, N., Moretti, R., Di Muro, A., Liuzzo, M., & Tamburello, G. (2010). A model of degassing for Stromboli volcano. Earth and Planetary Science Letters, 294, 195–204.

Aiuppa, A., Guidice, G., Liuzzo, M., Tamburello, G., Allard, P., Calabrese, S., et al. (2012). First volatile inventory for Gorely volcano, Kamchatka. Geophysical Research Letters, 39, L06307. https://doi.org/10.1029/2012GL051177

Bani, P., Harris, A. J. L., Shinohara, H., & Donnadieu, F. (2013). Magma dynamics feeding Yasur’s explosive activity observed using thermal infrared remote sensing. Geophysical Research Letters, 40, 3830–3835. https://doi.org/10.1002/grl.50722

Bobrowski, N., von Glasow, R., Aiuppa, A., Inguglia, S., Louban, I., Ibrahim, O. W., & Platt, U. (2007). Reactive halogen chemistry in volcanic plumes. Journal of Geophysical Research, 122, D06311. https://doi.org/10.1029/2006JD007206

Boichu, M., Oppenheimer, C., Tsanev, V., & Kyei, P. R. (2010). High temporal resolution SO$_2$ flux measurements at Erebus volcano, Antarctica. Journal of Volcanology and Geothermal Research, 190, 325–336.

Burton, M., Allard, P., Mure, F., & La Spina, A. (2007). Magmatic gas composition reveals the source depth of slug-driven Strombolian explosive activity. Science, 317, 227–230.

Caffiero, G., & Woods, A. W. (2016). Experiments on mixing in wakes in shallow water. Journal of Fluid Mechanics, 804, 351–369.

Delmelle, P., Wadsworth, F. N., Maters, E. C., & Ayris, P. M. (2018). Experiments on mixing in wakes in shallow water. Journal of Fluid Mechanics, 804, 351–369.

Dracos, T., Giger, M., & Jirka, G. H. (1992). Plane turbulent jet in a bounded fluid layer. Journal of Fluid Mechanics, 42, 587–614.

Edmonds, E., & Gerlach, T. M. (2007). Vapor segregation and loss in basaltic melts. Geology, 35, 751–754.
Hewett, T. A., Fay, J. A., & Hoult, D. P. (1971). Laboratory experiments of smokestack plumes in a stable atmosphere. *Atmospheric Environment, 5*, 767.

Hicks, K., Iacovino, K., Ilanko, T., Moussalam, Y., & Peters, N. (2012). *Field measurements of active volcanoes in the Southern Chilian Andes*. Field report in RGS. Retrieved from [https://www.rgs.org/CMSPages/GetFile.aspx?nodeguid=0ad491a-122-45d4-8915-cd1452a575f&clang=en-GB](https://www.rgs.org/CMSPages/GetFile.aspx?nodeguid=0ad491a-122-45d4-8915-cd1452a575f&clang=en-GB)

Ilanko, T., Pering, T. D., Wilkes, T. C., Apaza Choquehuayta, F. E., Kern, C., Diaz Moreno, A., et al. (2019). Degassing at Sabancaya volcano measured by UV cameras and the NOVAC network. *Volcanism, 2(2)*, 239–252.

Ilanko, T., Pering, T. D., Wilkes, T. C., Woitschek, J., D’Alleo, R., Aiuppa, A., et al. (2020). Ultraviolet camera measurements of passive degassing and explosive (Strombolian) sulphur dioxide emissions at Yasur Volcano, Vanuatu. *Remote Sensing, 12(17)*, 2703.

Jirka, G. H. (2001). Large scale flow structures and mixing processes in shallow flows. *Journal of Hydraulic Research, 39*(6), 567–573.

Kern, C., Werner, C., Elias, T., Sutton, A. J., & Luebcke, P. (2013). Applying UV-cameras for SO2 detection to distant or optically thick volcanic plumes. *Journal of Volcanology and Geothermal Research, 262*, 80–89.

Kroll, J. H. Cross, E. S., Hunter, I. F., Sidhant, P., TREX, X. II., TREX, XI., et al. (2015). Atmospheric evolution of sulfur emission from Kilauea: Real-time measurement of oxidation, dilution and neutralization within a volcanic plume. *Environmental Science and Technology, 49*, 4129–4137.

Landel, J. R., Caulfield, C. P., & Woods, A. W. (2012). Meandering due to large eddies and the statistically self-similar dynamics of quasi-two-dimensional jets. *Journal of Fluid Mechanics, 692*, 347–368.

Liu, E. J., Wood, K., Mason, E., Edmonds, M., Aiuppa, A., Guidice, G., et al. (2019). Dynamics of outgassing and plume transport revealed by proximal Unmanned Aerial Systems (UAS) measurements at Volcán Villarrica, Chile. *Geochemistry, Geophysics, Geosystems, 20*, 730–750. [https://doi.org/10.1029/2018GC007692](https://doi.org/10.1029/2018GC007692)

McGonigle, A. J. S., Delmelle, P., Oppenheimer, C., Tsanev, V. I., Delfosse, T., William-Jones, G., et al. (2004). SO2 depletion in tropospheric volcanic plumes. *Geophysical Research Letters, 31*, L13201. [https://doi.org/10.1029/2004GL019990](https://doi.org/10.1029/2004GL019990)

McGonigle, A. J. S., Delmelle, P., Oppenheimer, C., Tsanev, V. I., Delfosse, T., William-Jones, G., et al. (2005). SO2 depletion in tropospheric volcanic plumes. *Geophysical Research Letters, 31*, L13201. [https://doi.org/10.1029/2004GL019990](https://doi.org/10.1029/2004GL019990)

McGonigle, A. J. S., Pering, T. D., Wilkes, T. C., Tamburello, G., D’Alleo, R., Bitetto, M., et al. (2017). Ultraviolet imaging of volcanic plumes: A new paradigm in volcanology. *Geoscience, 7*, 68.

Morton, B. R., Taylor, G. I., & Turner, J. S. (1956). Turbulent gravitational convection from maintained and instantaneous sources. *Proceedings of the Royal Society of London A, 234*, 1–24.

Nadeau, P. A., & Williams-Jones, G. (2009). Apparent downwind depletion of volcanic SO2 flux—lessons from Masaya Volcano, Nicaragua. *Bulletin of Volcanology, 71*, 389–400.

Oppenheimer, C., Bani, P., Calkins, J. A., Burton, M. R., & Sawyer, G. M. (2006). *Rapid FTIR sensing of volcanic gases released by Stromboli*. Geosciences, *9*, 394.

Oppenheimer, C., Moretti, R., Kyle, P. R., Escchenbacher, A., Lowenstern, J. B., Hercig, G., et al. (2001). Large scale flow structures and mixing processes in shallow flows. *Journal of Fluid Mechanics, 39*(6), 261–271.

Papanicolaou, P. N., & List, E. J. (1988). Investigations of round vertical turbulent buoyant jets. *Journal of Fluid Mechanics, 195*, 341–391.

Pering, T. D., Ilanko, T., & Liu, E. J. (2019). Periodicity in volcanic gas plumes: A review and analysis. *Geoscience, 9*, 394.

Pering, T. D., Ilanko, T., Wilkes, T. C., England, R. A., Slotep, S. R., Stanger, L. R., et al. (2019). A rapidly convecting lava lake at Masaya Volcano, Nicaragua. *Frontiers of Earth Science, 6*, 241.

Pyplis Example video 1. (2017). SO2 emissions test dataset. YouTube video, added by Jonas Gliss [Online]. Retrieved from [https://www.youtube.com/watch?v=4lIXGF-xvQI](https://www.youtube.com/watch?v=4lIXGF-xvQI)

Sparks, R. S. J., Bursik, M. I., Carey, S. N., Gilbert, J. S., Glaze, L., Sigurdsson, H., & Woods, A. W. (1997). *Volcanic plumes*. John Wiley & Sons, Inc.

Tabazadeh, A., & Turco, R. P. (1993). Stratospheric chlorine injection by volcanic eruptions: HCl scavenging and implications for ozone. *Science, 260*, 1082–1086.

Tamburello, G., Aiuppa, A., Kantzas, E. P., McGonigle, A. J. S., & Rippe, M. (2012). Passive vs. active degassing modes at an open-vent volcano (Stromboli, Italy). *Earth and Planetary Science Letters, 249–260*, 106–116.

Tamburello, G., Aiuppa, A., McGonigle, A. J. S., Allard, P., Cannata, A., Guidice, G., et al. (2013). Periodic volcanic degassing behaviour: The Mount Etna example. *Geophysical Research Letters, 40*, 1–5. [https://doi.org/10.1002/grl.50924](https://doi.org/10.1002/grl.50924)

von Glasow, R. (2010). Atmospheric chemistry in volcanic plumes. *Proceedings of the National Academy of Sciences, 107*, 15730–15750. [https://doi.org/10.1029/2004GL019990](https://doi.org/10.1029/2004GL019990)

Wang, H., & Law, A. W. (2002). Second-order integral model for a round turbulent buoyant jet. *Journal of Fluid Mechanics, 459*, 397–428.

Woitschek, J., Edmonds, E., & Woods, A. W. (2020). The control of magma crystallinity on the fluctuations in gas composition at open vent basaltic volcanoes. *Scientific Reports, 10* (1), 14862. [https://doi.org/10.1038/s41598-020-71667-79f7b8b1-1637-47ae-bfbb-61cf3f2c2c19](https://doi.org/10.1038/s41598-020-71667-79f7b8b1-1637-47ae-bfbb-61cf3f2c2c19)

Woitschek, J., Woods, A. W., Edmonds, M., Oppenheimer, C., Aiuppa, A., Pering, T. D., et al. (2020). Strombolian eruptions and dynamics of magma degassing at Yasur Volcano (Vanuatu). *Journal of Volcanology and Geothermal Research, 398*, 106869.