# $SO_2$ Profiles During the Kilauea Eruption

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## Introduction

Kilaeua was in a significant eruptive phase in 2018 from early May to early August. During that period the flow of lava often reached the ocean from a series of fissures in the lower East Rift Zone. The resulting plume of volcanic smog (vog) contained mainly water vapor, sulfur dioxide ($SO_2$), and carbon dioxide. which is a global coolant when it reaches the stratosphere and is an irritant to the lungs leading to respiratory effects when present at the surface. A rapid response proposal, the Big Island $SO_2$ Survey (James Flynn (PI)), was funded by NASA to test improvements to the newly developed single-pump $SO_2$ sonde by collecting a series of vertical profiles. During the two-week intensive in late June 2018 nine improved single-pump $SO_2$ sondes were flown in addition to three drives with the sonde and an instrumented van.

The Kahuku Ranch (~90 km downwind) was the primary launch location for the June deployment, chosen to allow the plume to disperse somewhat to help avoid saturating the sonde (Figures 2 and 3). Under conditions such as these where [$SO_2$] was expected to be much greater than [$O_3$] the dual-sonde method was not expected to perform well therefore none were flown.

Figure 1. June 2018 field team: Mark Spychala (left), Paul Walter (2nd from left), James Flynn (2nd from right), and Elizabeth Klovenski (right).

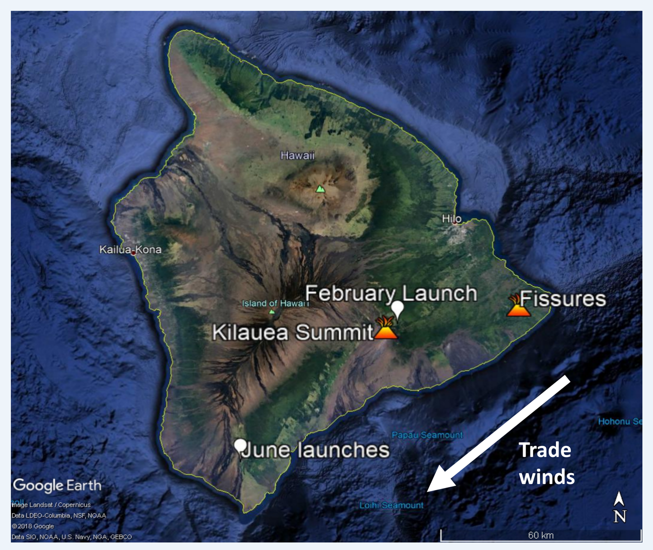


Figure 2. Map of the Big Island of Hawaii showing the locations of key features and launch site locations. In June trade winds brought the plume to southern Hawaii.

## Dual-sonde method

In electrochemical cell (ECC) ozonsondes, $SO_2$ interferes with ozone ($O_3$) sondes on a 1-to-1 basis, i.e. 1 ppbv $SO_2$ = -1 ppbv $O_3$. The dual-sonde method for measuring vertical profiles of $SO_2$ from balloons relied on using two $O_3$ sondes where the second sonde samples through a $SO_2$ scrubbing filter. The $SO_2$ profile is then calculated by subtracting the unfiltered sonde data from the filtered sonde. This method can work well in the troposphere when [$SO_2$] < [$O_3$]. When [$SO_2$] exceeds [$O_3$] the unfiltered sonde saturates and reports zero, distorting the $SO_2$ profile.

## Single-pump $SO_2$ sonde

Beginning in late 2016 a new method for direct measurements of $SO_2$ using a single sonde was developed by the University of Houston (Flynn) and St. Edward's University (Morris). The new sonde can measure $SO_2$ regardless of $O_3$ levels as ambient $O_3$ is removed from the sample stream. This approach is able to measure [$SO_2$] >> [$O_3$] without saturating and can be configured for a sub-ppbv LLOD. Prior field tests of the single-pump $SO_2$ sonde were carried out in February 2018 on the Big Island of Hawaii in at the same time as the NASA HyspIRI HyTES campaign and in March 2018 in San Jose, Costa Rica as part of the NASA Ticosonde project.

Figure 3. Launch of single-pump $SO_2$ sonde at Kahuku Ranch located at the "June launches" site on Figure 2.

## Turrialba, Costa Rica (March 2018): Comparison of dual sonde to single pump $SO_2$ sonde

In March 2018 the UH (Flynn) and SEU (Morris and Spychala) team flew a free release flight from the Universidad de Costa Rica (UCR) campus in San Jose (~31 km downwind of Turrialba) with a payload of a traditional dual-sonde as well as the new single-pump $SO_2$ sonde (Figure 4). Figure 5 shows the response of the three sondes and the calculated $SO_2$ profile using the dual-sonde method. The unfiltered $O_3$ sonde (blue) saturated when [$SO_2$] exceeded [$O_3$], resulting in a distorted profile (green), while the $SO_2$ sonde was able to measure [$SO_2$] >> [$O_3$] and capture the full shape of the profile. This was the first successful launch of a dual-sonde and new single-pump $SO_2$ sonde on the same payload, allowing for a direct comparison of the methods. The vertical column density (VCD) of the single-pump $SO_2$ sonde was 8.3 DU while it was 3.4 DU for the dual-sonde. The single-pump $SO_2$ sonde showed no interference from $O_3$, even though the flight reached 30 km and the stratospheric $O_3$ layer.

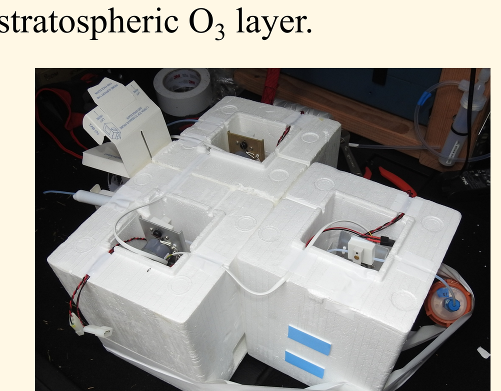

Figure 4. Dual sonde: $O_3$ sonde (rear), $O_3$ sonde with $SO_2$ filter (left); $SO_2$ sonde (right).

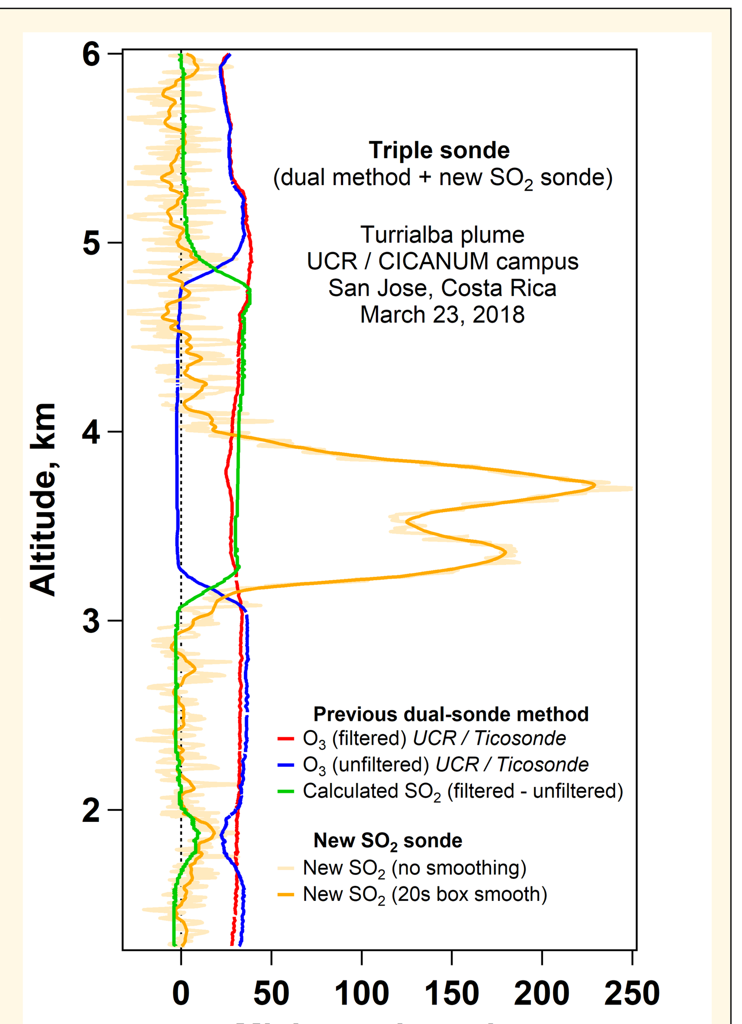


Figure 5. March 23, 2018 $SO_2$ profile from the UCR campus ~31 km downwind of the Turrialba volcano. The payload consisted of the traditional dual-sonde and the new single-pump $SO_2$ sonde. The dual-sonde saturated while the plume was captured by the single-pump $SO_2$ sonde.

## Big Island $SO_2$ Survey (June 2018)

An $SO_2$ plume detected on most of the nine flights of the single-pump $SO_2$ sonde. Eight profiles are presented here (Figure 6) showing the lowest 5 km of each profile. At altitudes above 5 km reductions in air density begin to significantly impact the detection limits of the sonde for the configuration used in this study.

In order to measure the high levels of $SO_2$ that were anticipated, the sondes were configured for the maximum upper limit of detection, typically 400-500 ppbv, at the expense of the lower detection limit. The first flight on June 30, 2018 (profile F) was the only time when the single-pump $SO_2$ sonde saturated. The launch times and vertical column density (VCD) of the flights are shown in the table below.

| Profile | Launch Time (UTC) | $SO_2$ VCD |
|---|---|---|
| **A** (ascent) | 06/22/2018 00:32 | 8.6 DU |
| **B** (ascent) | 06/24/2018 23:17 | 3.9 DU |
| **C** (ascent) | 06/26/2018 23:28 | 14.1 DU |
| **D** (ascent) | 06/28/2018 20:45 | 12.5 DU |
| **E** (descent) | 06/29/2018 21:36 | 9.8 DU* |
| **F** (ascent) | 06/30/2018 20:48 | 79.1 DU |
| **G** (ascent) | 06/30/2018 23:38 | 9.9 DU |
| **H** (descent) | 07/01/2018 01:47 | 7.7 DU |

(* includes linear extrapolation to sea level)

In each of these profiles the majority of the $SO_2$ plume was found within the mixed layer, with the peak typically found between 1-2 km and rarely exceeding 3 km. While initial flights used 600 g balloons reaching over 25 km it was quickly determined that smaller 350 g balloons would conserve helium and increase the likelihood of encountering the plume in the descent by avoiding upper level winds.

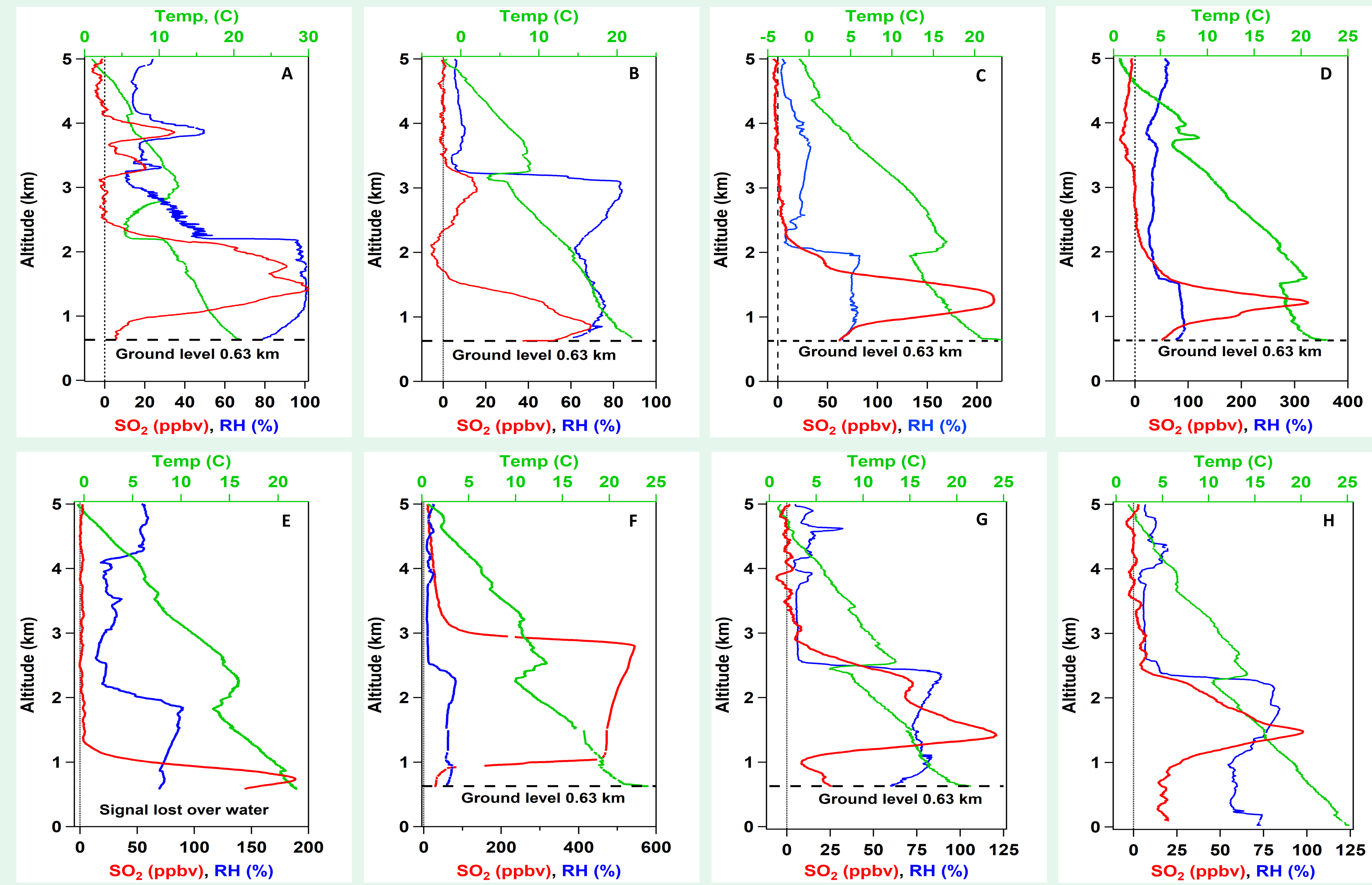


Figure 6. Vertical profiles of $SO_2$ from the improved single pump $SO_2$ sonde during the Big Island $SO_2$ Survey in June 2018. Letters correspond to vertical column densities in the table and are also shown in Figure 9. Profile F is of the only flight where the sonde saturated.

## $SO_2$ measurements while driving

An in situ $SO_2$ monitor (Thermo 43c-TL) was installed in the minivan and time series data through the June 2018 campaign (see Figure 9) and also when driving. On June 22, 2018 (Figure 7), the drive left the Kahuku Ranch near the southern part of the island and went clockwise with a midday stop at the Mauna Loa Observatory at which point we were at altitudes well above the $SO_2$ plumes from the Kilauea eruption. While there is significant spatial and temporal variability in the $SO_2$ levels at the surface (see the green line in Figure 9), the highest levels during the drive being observed on the southwest portion of the island is consistent with the Trade Winds blowing the Kilauea plume in that direction. On July 1, 2018 (Figure 8), we drove from the southernmost point of the island uphill and eventually passed into some of the $SO_2$ plume.

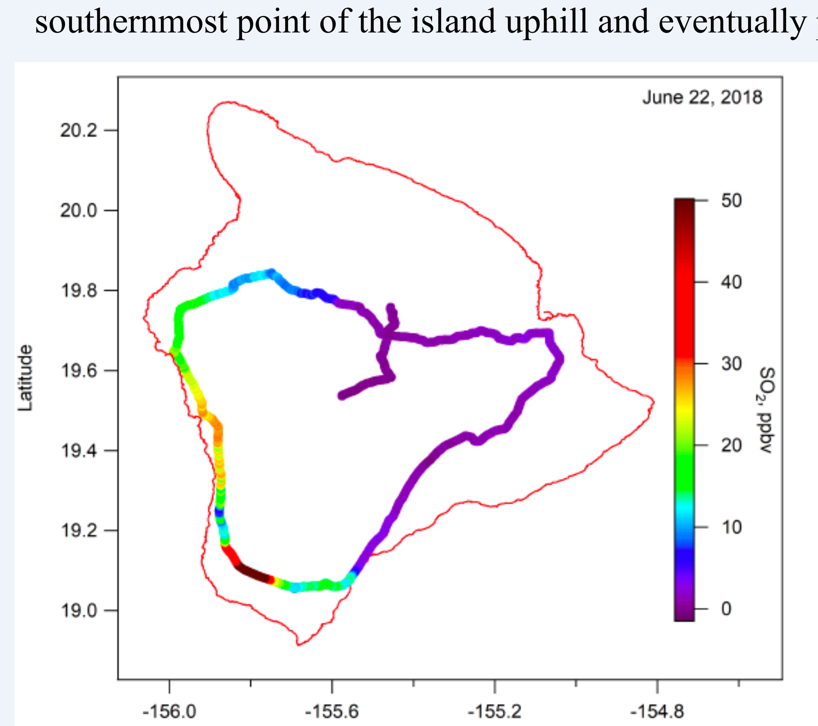


Figure 7. $SO_2$ measurements while driving around the Big Island of Hawaii and June 22, 2018. The loop included a stop at the Mauna Loa Observatory.

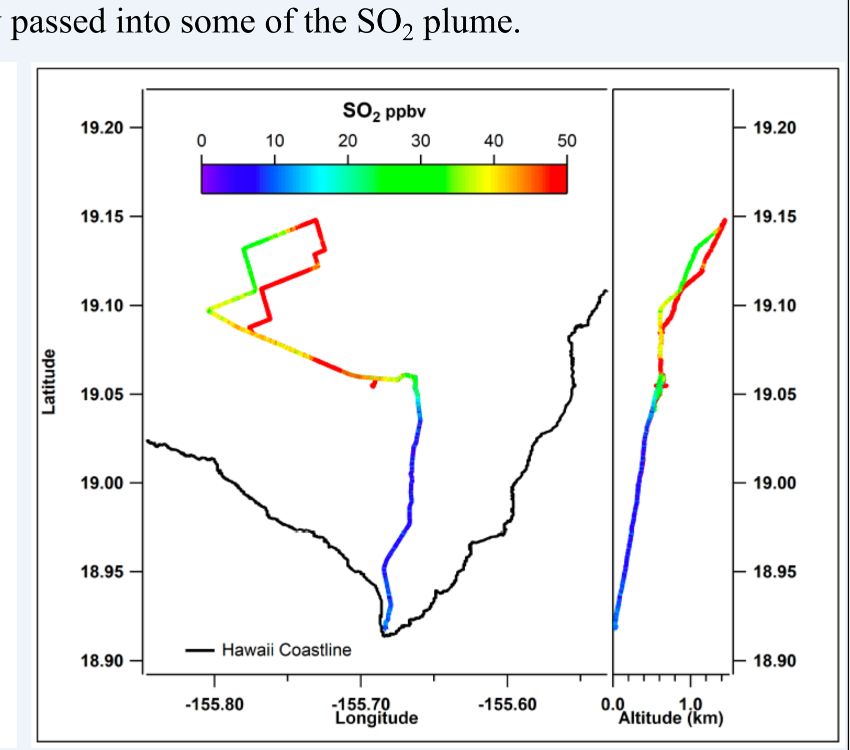


Figure 8. $SO_2$ measurements while driving near the South Point of the Big Island of Hawaii on July 1, 2019. During the drive we went vertically in altitude.

## Total Column $SO_2$ Comparison with Pandora

A Pandora spectrometer (P60) was mounted to the roof of the minivan operating in zenith mode to measure the vertical column density (VCD) of $SO_2$. A time series of in situ $SO_2$ measured by the Thermo 43c-TL, preliminary Pandora VCD, and integrated $SO_2$ sonde VCD shows that the integrated sonde VCD tracks well with the Pandora VCD.

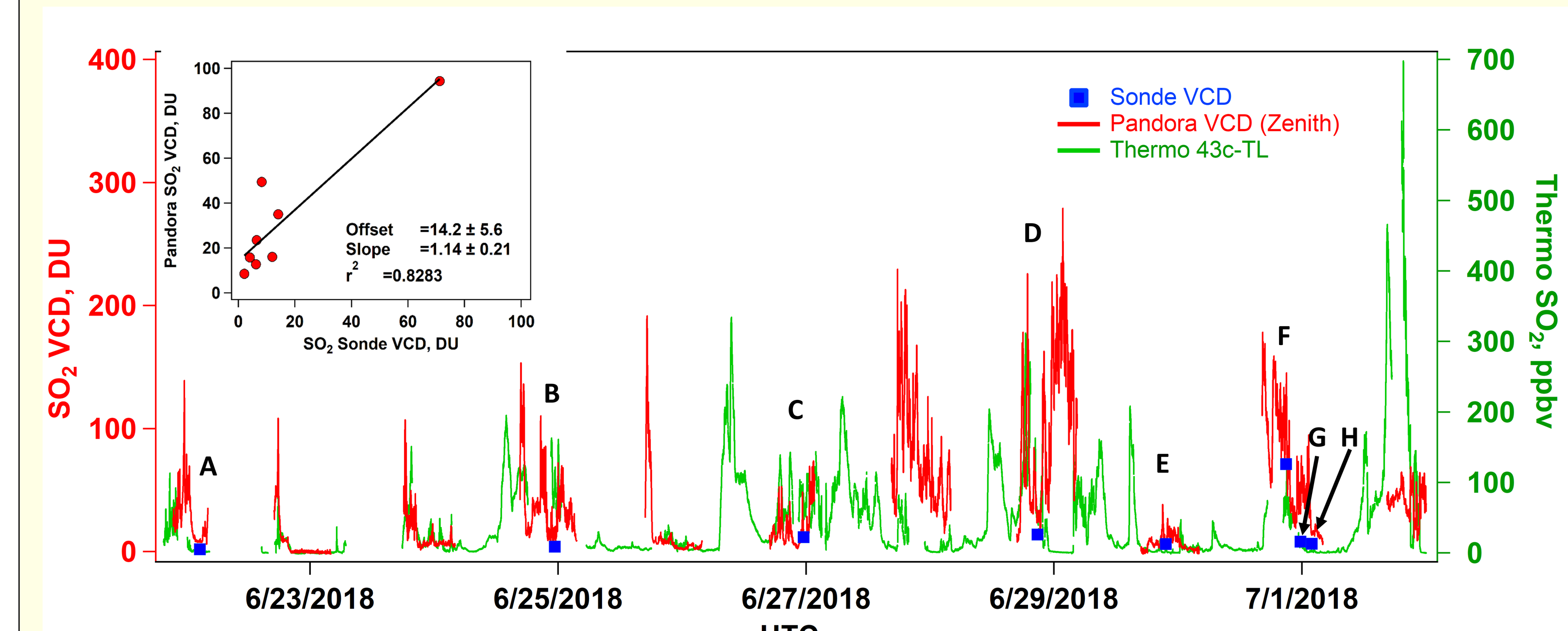


Figure 9. Integrated VCD from the $SO_2$ sonde and Pandora spectrometer with in situ $SO_2$ measurements. While the Pandora VCD is preliminary, the general agreement is promising.

## Conclusions and Future Work

The Kilauea eruption offered an excellent testbed for the ongoing improvements to the single-pump $SO_2$ sonde. The $SO_2$ plume resulting from the Kilauea eruption typically did not exceed altitudes of 3 km. Locating the altitudes of the plumes (in particular, all descents of sondes occurred over the ocean) can aide the calibration of satellite measurements.

Future work includes performing analysis of satellite data to compare VCD measurements between the sonde, Pandora, and satellite. Flynn and collaborators are working on further improvements of the single-pump $SO_2$ sonde to increase the upper detection limit and dynamic range of the sonde while maintaining the lower limit of detection below 1 ppbv and making the sonde commercially available.

## References

Morris, G. A., W. D. Komhyr, J. Hirokawa, J. Flynn, B. Lefer, N. Krotkov, and F. Ngan (2010), A Balloon Sounding Technique for Measuring $SO_2$ Plumes, Journal of Atmospheric and Oceanic Technology, 27(8), 1318-1330, doi:10.1175/2010jtecha1436.1.

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