Study of the changes in SO_2 emissions flux in plumes from Popocatepetl in Mexico during 2015 through 2016, using OMI sensor images aboard NASA's Aura satellite

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Abstract

Popocatepetl volcano is one of the most active volcanoes in Central Mexico, at 19.02° N and 98.07° W, and has an elevation of 5465 meters above sea level. This stratovolcano is part of the Trans-Mexico Volcanic Belt. After being dormancy between 67-70 years, Popocatepetl started to erupt on December 21, 1994. The monitoring of volcanic emissions of gases is very important because a gives information about evolution of volcanic systems, helping to reduce volcanic risk and understand volcanic processes. During a volcanic eruption the principal gases emitted are sulfur dioxide (SO_2), water vapor (H_2O) and carbon dioxide (CO_2). SO_2 is the third volcanic gas most abundant, before of the H_2O and CO_2. The principal objective of this investigation is studying the changes of the sulfur dioxide in the plumes of the Popocatépelt volcano in Mexico, using the images of the sensor OMI during 2015-2016.

Key words: OMI, SO_2 cloud mass, SO_2 flux, Popocatépetl volcano

Introduction

Volcano monitoring is a set of techniques that allow the measurement of different parameters (seismic, geodetic, thermal, geochemical, gas emissions, etc., Figure 1) in a volcano. It is important for the mitigation of volcanic risk, since it allows knowing the state of the internal and external activity of a volcano in time and thus detect anomalies that can lead to an eruption, changes during the course of an eruptive cycle or even to understand the operation of a volcano. (Romero et al., 2018).

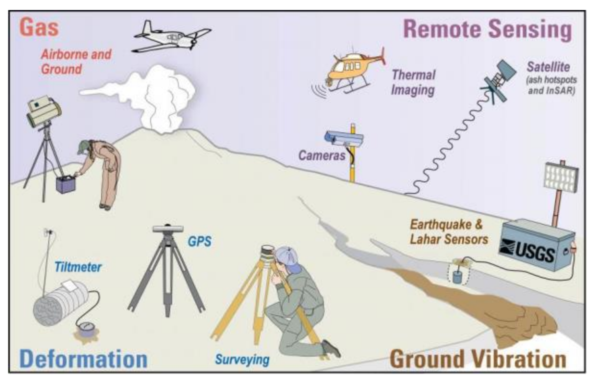

Figure 1. Different techniques of volcanic monitoring (Romero et al., 2018; Faust, USGS).

Gas monitoring can be, by remote sensing on the surface and by satellite remote sensing (Rodriguez and Nadeau et al., 2015).

"Measurements of volcanic gas emissions can provide important information on the dynamics and evolution of magmatic systems" (Rodriguez and Nadeau et al., 2015; Stoir et al., 1983; Aiupp et al., 2002, Allard et al., 2005; Sawyer et al., 2008).

The elements that are dominant in a volcanic plume are C, O, H, S, Cl, Br, F and Si, which combine to form more abundant species of gases: water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrochloric acid (HCl) and fluorohydrin acid (HF) (Rodriguez and Nadeau et al., 2015).

SO_2 is the third most abundant volcanic gas, after H_2O and CO_2 (Rodriguez and Nadeau et al., 2014). The degassing of sulfur (S) from volcanoes is important because it can substantially influence magmatic evolution, to the point of triggering eruptions (Rodriguez and Nadeau et al., 2014; Oppenheimer et al., 2011a). Sulfur dioxide causes damage to terrestrial ecosystems (acid rain) (Rodriguez and Nadeau et al., 2014, Delmelle, 2003) and has negative effects on human health (difficulty in breathing, inflammation of the respiratory tract) (Rodriguez and Nadeau et al., 2014; Hansell & Oppenheimer et al., 2006).

Popocatépetl volcano is located in central Mexico at the volcanic front of the Trans-Mexican Volcanic Belt, around Popo is located cities, Atlixco, Cuautla, Cuernavaca, Puebla, Amecameca, Chalco and Mexico City (figure 2 and 3) (Delgado- Granados et al., 2008). This active volcano located approximately in latitude 19.02º N and longitude 98.62º W (Grutter et al., 2008). Its elevation is ~5465 meters above sea level (Kotsarenko et al., 2007). Popocatepetl is an andesitic stratovolcano and is part of Trans-Mexican volcanic belt (Delgado-Granados, 2008), which results from subduction of the Cocos plate under the North American plate (Figure 4) (Nin- Hernández et al., 2013; Gómez-Tuena et al., 2007). The total population around Popocatepetl is ~20 million inhabitants, which are exposed constantly to different volcanic hazard (Delgado-Granados, 2008).

Figure 2. Popcatépetl volcano quiet during January 2005 (Image from Kotsarenko et al., 2007).

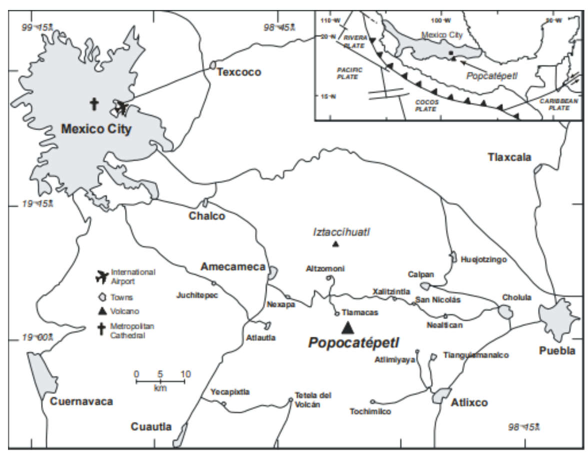

Figure 3. Towns around of Popocatepetl volcano. The Trans-Mexican volcanic belt is showed in the upper part of the figure (Delgado-Granados et al., 2008).

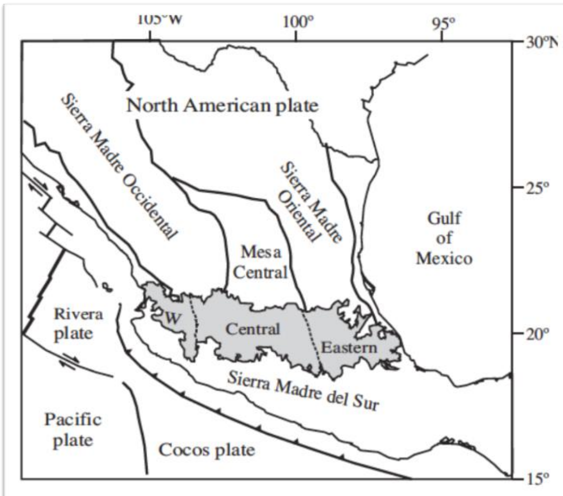

Figure 4. This figure that shows the Trans-Mexican volcanic belt (in gray). The map also shows the area of subduction of the Cocos plate under North American plate (Figure from Nin-Hernández et al., 2013; Gómez-Tuena et al., 2007).

Popocatépetl was dormant for approximately 67 years, but in December 21, 1994 it became active with eruption (Delgado-Granados et al., 2008). This explosion was characterized by a vulcanian phase consisting of strong explosions that opened the conduits and produced ballistic fallout within 1 km from the vent on the eastern flank of the edifice, accompanied by ash falls (Delgado-Granados et al., 2008). The ash falls continuous for several day and more than 24,000 people were evacuated during first days of activity, and nearly 70,000 people left their home approximate 2-3 weeks (Delgado- Granados et al., 2008). This explosion destroyed the small lake that was nested in the interior of the crater (Delgado-Granados et al., 2008).

Popocatepetl activity declined during 1995 (Delgado-Granados et al., 2008). "Sporadic explosion with emissions of ash were typical of this phase" (Delgado-Granados et al., 2008). In August 1995, the ash emissions stopped. In August-September 1995 to March 1996 there were no ash emissions (Delgado-Granados et al., 2008). On April 30, 1996, another explosion occurred which killed five people who had illegally climbed to the top of the volcano (Delgado-Granados et al., 2008).

The most recent activity of the Popocatépelt volcano is the past month March 14, 2019, where register explosion that generate a column 5 km high, with high content of ash. On March 22, the same year, presenting a explosion that generate column of ashes, water vapor and gas.

The principal objective of this investigation is studying the changes of the sulfur dioxide in the plumes of the Popocatépelt volcano in Mexico, using the images of the sensor OMI during 2015-2016. The second objective is calculating the mass of the SO_2 cloud in order to determine the flux of SO_2 in a given time. In this research also includes images of the explosion of March 14, 2019, to see the activity of the volcano before and after an explosion.

Methodology

This research had three different stages: (1) downloading, processing and analysis of OMI images, (2) determining the mass of the SO_2 cloud to determine the flux of SO_2 during 2015-2016, and (3) also determining the mass of the SO_2 cloud to determine the flux of SO_2 during explosion March 14, 2019, to observed the activity of the volcano before and after explosion.

Ozone Measurement Instrument (OMI)

This investigation was based on the study of satellite images from Ozono Monitoring Instrument (OMI). OMI is onboard the Aura satellite from NASA that was launched in July 2004 (Carn et al., 2013). OMI sensor covers ultraviolet (UV, 270-500 nm) and visible spectral wavelengths (350-500 nm), with a spatial resolution of 13x24 km^2 (Carn et al., 2013). This sensor has a swath of 2600 km (Figure 5) (NASA et al., 2009). Aura satellite orbits at an altitude of 705 km in a sun-synchronous polar orbit with an exact 16-day repeat cycle (NASA et al., 2009).

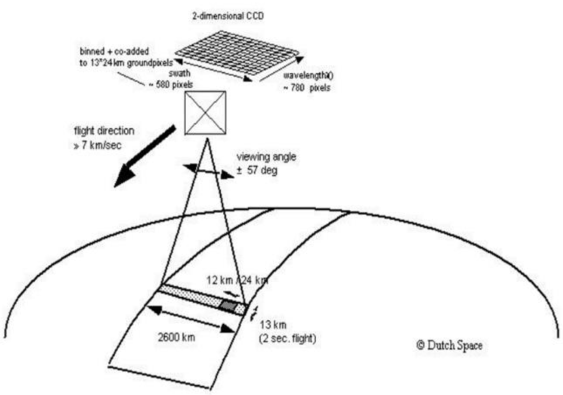

Figure 5. OMI sensor (NASA et al., 2009).

Twelve images from OMI were downloaded and processed in this research, from 2015-2016 (chosen an image obtained every three months (January, April, August and December) where there is a plume from the Popocatépetl volcano) and 2019 (chosen an image before and after explosion). The OMI images were downloaded from NASA data archives ((http://disc.sci.gsfc.nasa.gov/Aura/OMI/omso2_v003.shtml). OMI image was processed with the OMIplot program, in the Environment for Visualizing Images-Interactive Data Language (ENVI-IDL) software (Carn et al., 2011). OMIplot is a software package which produces images for different atmosphere elevations (vertical profiles): Planetary Boundary Layer (PBL) for 1 km, TRL for 3 km (lower tropospheric), TRM for 5 km (middle tropospheric), and STL for 15 km (upper tropospheric and stratospheric) (Carn et al., 2011). OMIplot also produces image a cloud fraction and aerosol index. The SO_2 data in the OMI images are in Dobson Units (DU). This unit it is a way of expressing the present amount of ozone in the Earth's atmosphere (1 DU= $2.69x10^{16}$molecules/cm^2).

Calculation of SO_2 cloud mass

To determine the SO_2 cloud mass two areas are chosen in the OMI image (TRM 5 km), using OMIplot: the first area including the plume and the second area for the background (Carn et al., 2011). The area chosen for the background should have similar meteorological conditions to the plume area (determined by using the cloud fraction image; this area cannot have cloudiness). The equation to determine the SO_2 cloud mass includes the following variables: SO_2 mass in the plume (SO_{2cloud}), plume area (A_{cloud}), SO_2 mass in the background (SO_{2back}), and the background area (A_{back}) (Carn et al., 2011):

$$SO_2 \text{ cloud mass} = SO2_{cloud} - \left(\frac{A_{back}}{A_{cloud}} \times SO2_{back}\right)$$

SO_2 flux measurements

The SO_2 flux significate the rate at which a volcano releases SO_2 to the atmosphere and is usually calculated in tons per day (Nin et al., 2013; Sutton et al., 1992). To determine the SO_2 fluxes in this research were using the multiple pixels for the calculation. The SO_2 flux into multiple pixels is calculated using the SO_2 mass in the plume area (M, from the SO_2 cloud mass calculation), the wind speed (WS) (The wind speed that was used was that of the selected month of the chosen image) and the length of the plume in the multiple pixels (L) (Carn et al., 2013):

$$SO_2 \text{ flux} = [\frac{M \ x \ WS}{L}]$$

For this investigation, I used the wind speed of the nearest meteorological station to the Licenciado Benito Juarez airport in Mexico City.

Results and discussion

The results of this research include the OMI images and the calculation of SO_2 mass and flux. The dates in the period of study were chosen according to the activity in the volcano for 2015-2016 and 2019 (chosen image where there are plume). The specific dates selected for 2015-2016 and 2019 are included in table 1, table 2 and 3.

Change on SO_2 flux from 2015-2016 in Popocatépetl, Mexico

Figure 6 shows an increase in the flux of SO_2 in 2015, where on January 20 it had a flux of 826.5049304 t / days, then continued to increase and on August 21, it had a flux of 4738.639508 t / day the highest flux between the selected months and days and suddenly there is a decrease in SO_2 flux.

For the year 2016, the flux of SO_2 remains constant. On January 23, 2016 a flux of 17888.860895 t / days was reported, this being the highest of that year. On August 30, it was the lowest flux for 2016 with 1110.749393 t / days.

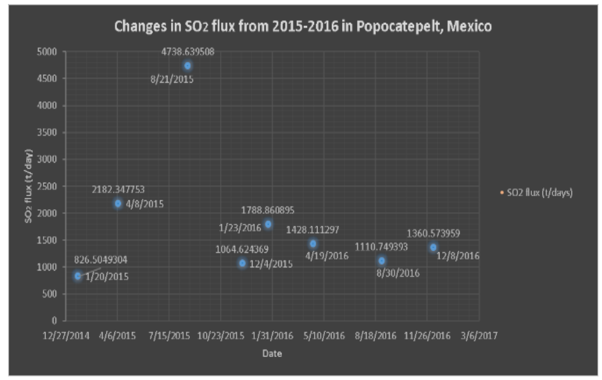

Figure 6. Change in SO_2 flux from 2015-2016 in Popocatépelt, Mexico.

August 21, 2015

According to seismic records of the volcano monitoring system, 26 exhalations of very low intensity were identified, which were accompanied by slight emissions of water vapor and gases (CENAPRED et al., 2015). The plume of August 21, 2015 is observed just above the volcano, which may be indicative that to that day the wind speed was slight (figure 7 and figure 8).

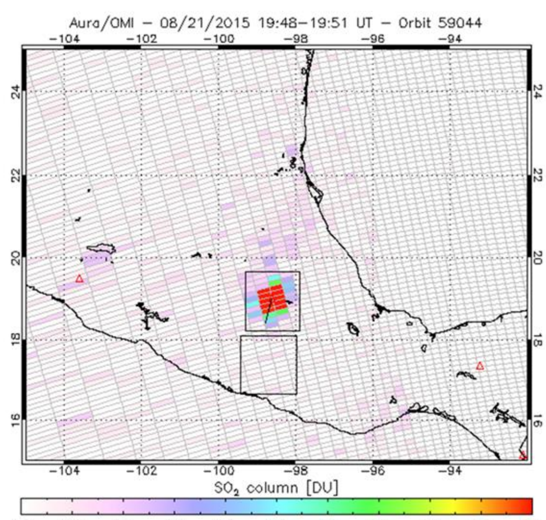

Figure 7. OMI image showing the 5 km vertical profile for August 21, 2015.

Figure 8. Photo of the plume of the Popocatepetl volcano (CENAPRED, 2015).

August 30, 2016

According to the report, 185 low intensity exhalations were identified, accompanied by emissions of water vapor, gas and light quantities of ash, and explosion at 09:49 h (figure 9) (CENAPRED et al., 2016). In the OMI TRL image (5 km) the plume that is observed in the image moves towards the southwest (figure 10).

Figure 9. Explosion of August 30, 2016 at 9:49 h.

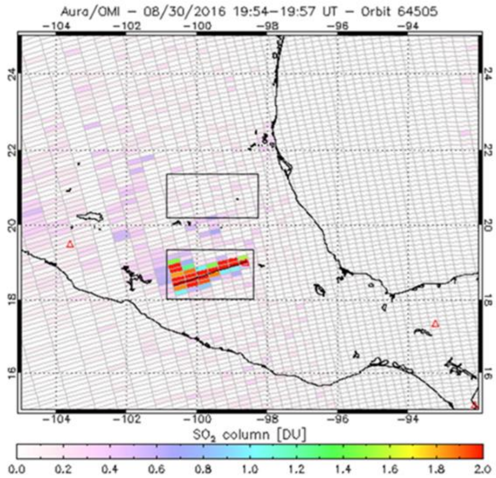

Figure 10. OMI image showing the 5 km vertical profile for August 30, 2016.

Changes in SO2 mass (tons) and Flux (t/days) before and after March 14, 2019 Explosion

In figure 11 we have the relation between the mass and the flux of SO_2, where three days before the explosion of March 14, 2019, a decrease in SO_2 flux is observed, causing the accumulation of gases to a point that could no longer be retain more gas, causing the explosion on March 14. After the explosion the flow of SO_2 continued to decrease although the mass increased, this could have happened due to the length of the plume or the wind speed.

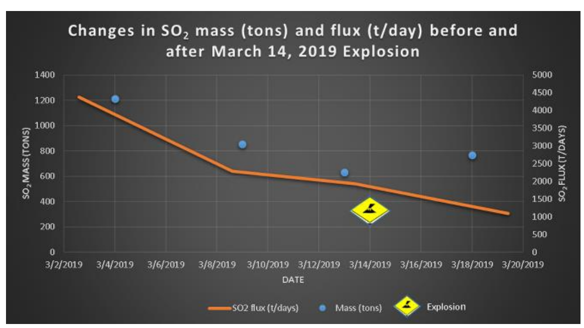

Figure 11. Changes in SO_2 mass (tons) and flux (t/day) before and after March 14, 2019 Explosion.

Explosion of March 14, 2019

On March 14, 2019, an explosion occurred at 14:30h, generating a column 5 km high, with a high ash content, moving in a north-northeast direction (figure 12) (CENAPRED et al., 2019). According to the Popocatepetl volcano monitoring systems, 61 low intensity exhalations were identified, accompanied by a continuous emission of water vapor, gas and light amounts of ash (CENAPRED et al., 2019).

Figure 12. Explosion of March 14, 2019 (CENAPRED et al., 2019).

Conclusion

Volcano monitoring is important for the mitigation of volcanic risk, since it allows knowing the internal and external activity of the volcano in order to detect anomalies that can lead to an explosion, with the help of remote sensors you can obtain different information to be used by the authorities civilians, warning centers and for the community in general, especially for populations that are exposed to these risks.

Based on the processing of the images in the ENVI-IDL program, there was an increase in the flux of SO_2 from January to August, where on August 21, 2015 there was a flux of 4738.63 t / day, after this date there was a decrease. In 2016, the flux of SO_2 remained constant, with the lowest flux being reported on August 30, 1110.74 t / day.

In the event of March 14, 2019, days before the explosion occurred, a decrease in the flux of sulfur dioxide was observed, where on March 13 (the day before the explosion occurred) a flux of 1930.14 t/ days was reported. This may have accumulated gases, causing the explosion.

Recommendations

For future work, perform the technique of the transects, to compare which is more accurate when determining the flux of the sulfur dioxide cloud. Compare surface remote sensing with satellite remote sensing. Use the daily wind speeds for the selected days to obtain more specific data.

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Tables

Date	Plume mass (SO_2 cloud) (kt)	Plume area (A cloud) (Km^2)	Background SO_2 mass (SO_2 back) (kt)	Background area (A back) (Km^2)	SO_2 Cloud Mass (kt)	Mass (tons)	Wind (Km/h)	Wind (m/s)	Plumes length (km)	Plumes length (m)	SO_2 flux (t/s)	SO_2 flux (t/days)
1/20/2015	1.14242	51812.2	-0.0223517	56194.2	1.167	1166.66209	9.7	2.69444444	328.61139	328611.39	0.00956603	826.50493
4/8/2015	3.28423	140772	0.0315567	81171.6	3.266	3266.03385	11.2	3.11111111	402.27773	402277.73	0.02525865	2182.34775
8/21/2015	1.03488	23921.3	-0.0110104	24210.3	1.046	1046.02342	12.8	3.55555556	67.812374	67812.374	0.05484536	4738.63951
12/4/2015	1.53413	76550.7	0.0151692	71658.1	1.520	1519.93031	9.5	2.63888889	325.50834	325508.34	0.01232204	1064.62437

Table 1: Table that shows the parameters used in the calculation of SO_2 cloud mass and SO_2 flux for 2015.

Date	Plume mass (SO_2 cloud) (kt)	Plume area (A cloud) (Km^2)	Background SO_2 mass (SO_2 back) (kt)	Background area (A back) (Km^2)	SO_2 Cloud Mass (kt)	Mass (tons)	Wind (Km/h)	Wind (m/s)	Plumes length (km)	Plumes length (m)	SO_2 flux (t/s)	SO_2 flux (t/days)
1/23/2016	4.69609	136489	0.09376	126606	4.609119046	4609.11905	9.7	2.69444444	599.82468	599824.68	0.02070441	1788.86089
4/19/2016	1.54784	60449.7	-0.0749313	58248.4	1.620042647	1620.04265	11.1	3.08333333	302.20289	302202.89	0.01652907	1428.1113
8/30/2016	0.974905	38734.5	0.00381534	36045.8	0.971354496	971.354496	10.7	2.97222222	224.57256	224572.56	0.0128559	1110.74939
12/8/2016	2.28631	113087	-0.070286	112151	2.356014256	2356.01426	10	2.77777778	415.59183	415591.83	0.01574738	1360.57396

Table 2: Table that shows the parameters used in the calculation of SO_2 cloud mass and SO_2 flux for 2016.

Date	Plume mass (SO_2 cloud) (kt)	Plume area (A cloud) (Km^2)	Background SO_2 mass (SO_2 back) (kt)	Background area (A back) (Km^2)	SO_2 Cloud Mass (kt)	Mass (tons)	Wind (Km/h)	Wind (m/s)	Plumes length (km)	Plumes length (m)	SO_2 flux (t/s)	SO_2 flux (t/days)
3/4/2019	1.19988	60630.6	-0.0140833	56691.7	1.213048371	1213.04837	29.6	8.22222222	196.61704	196617.04	0.05072782	4382.88341
3/9/2019	0.879794	42983.4	0.0248465	43558.9	0.854614833	854.614833	22.2	6.16666667	199.62642	199626.42	0.02639994	2280.95451
3/13/2019	0.739323	54285.7	0.118598	49964.5	0.630165528	630.165528	33.3	9.25	260.92833	260928.33	0.02233959	1930.14032
3/18/2019	0.834304	105583	0.0728027	96276.9	0.76791814	767.91814	24.1	6.69444444	407.98913	407989.13	0.0126003	1088.6659

Table 3: Table that shows the parameters used in the calculation of SO_2 and SO_2 flux for 2019.

Figures

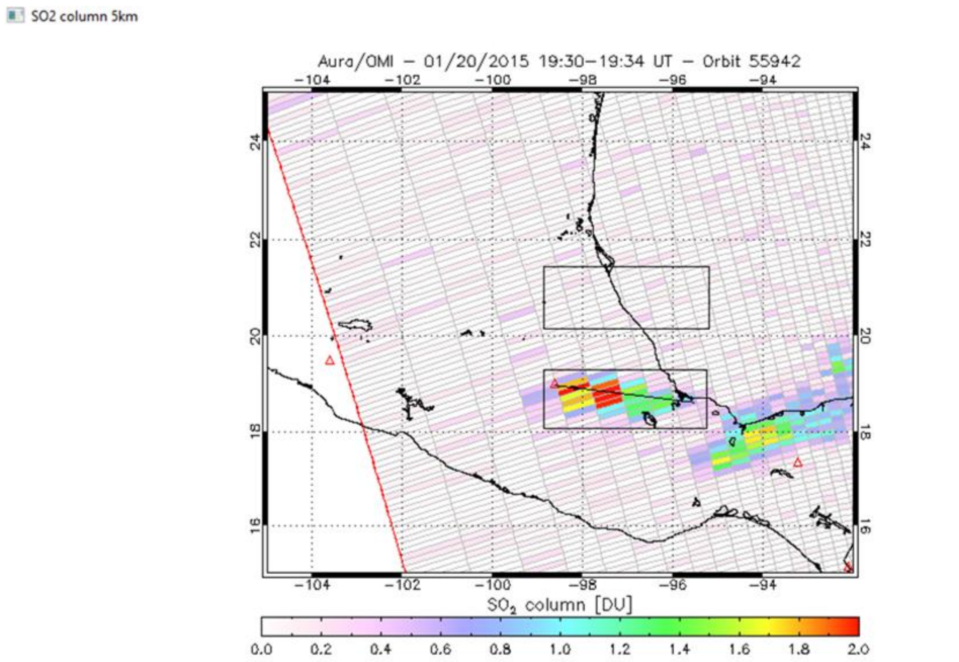

Figure 1. OMI image showing the 5 km vertical profile (TRM) for January 20, 2015.

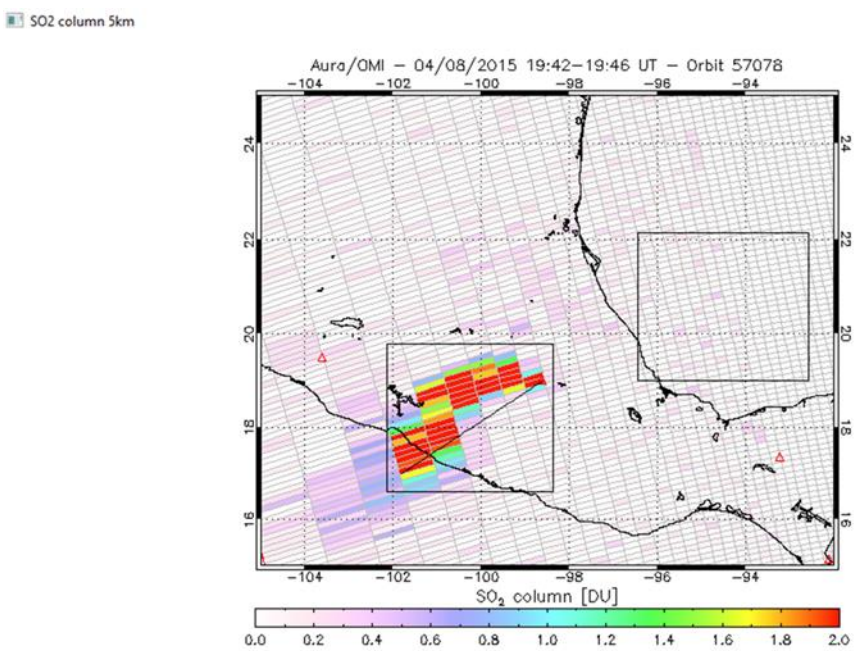

Figure 2. OMI image showing the 5 km vertical profile (TRM) for April 8, 2015.

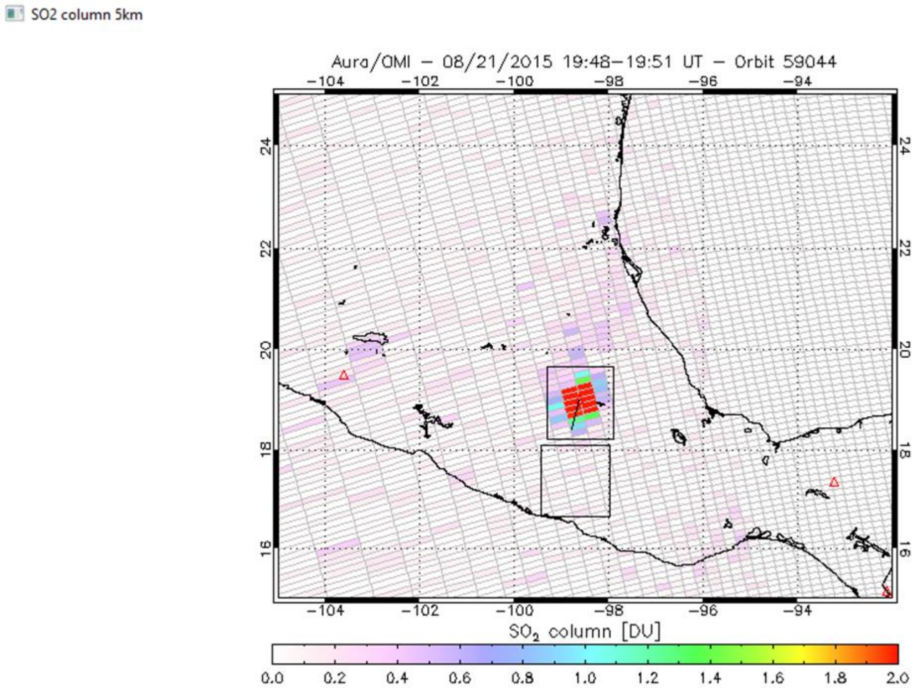

Figure 3. OMI image showing the 5 km vertical profile (TRM) for August 21, 2015.

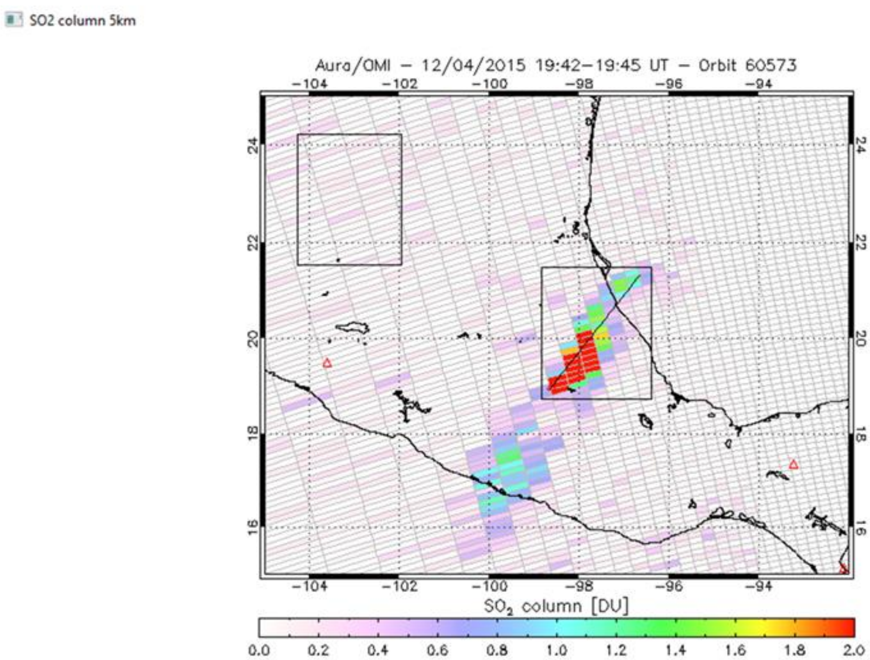

Figure 4. OMI image showing the 5 km vertical profile (TRM) for December 4, 2015.

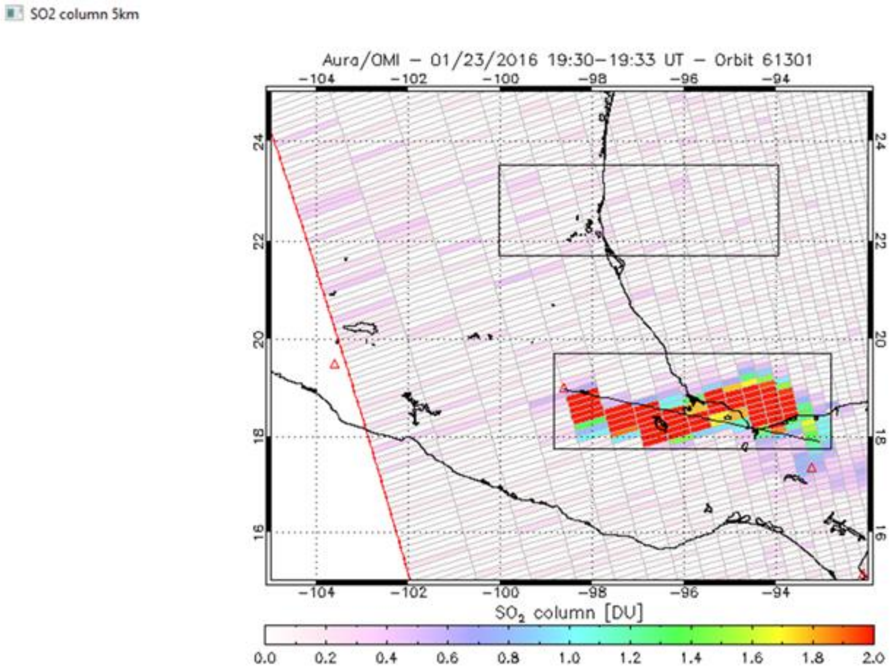

Figure 5. OMI image showing the 5 km vertical profile (TRM) for January 23, 2016.

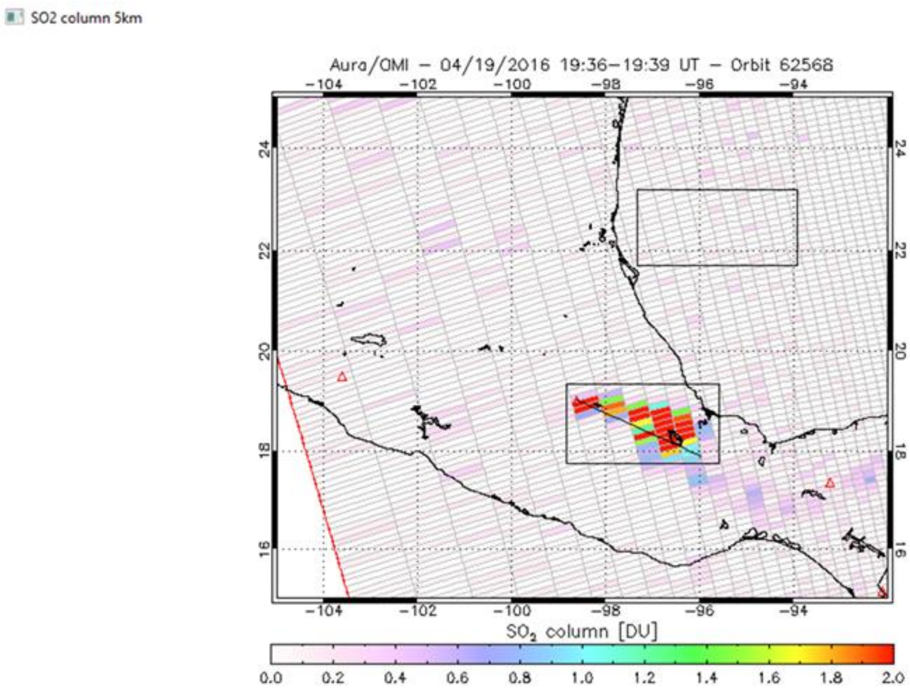

Figure 6. OMI image showing the 5 km vertical profile (TRM) for April 19, 2016.

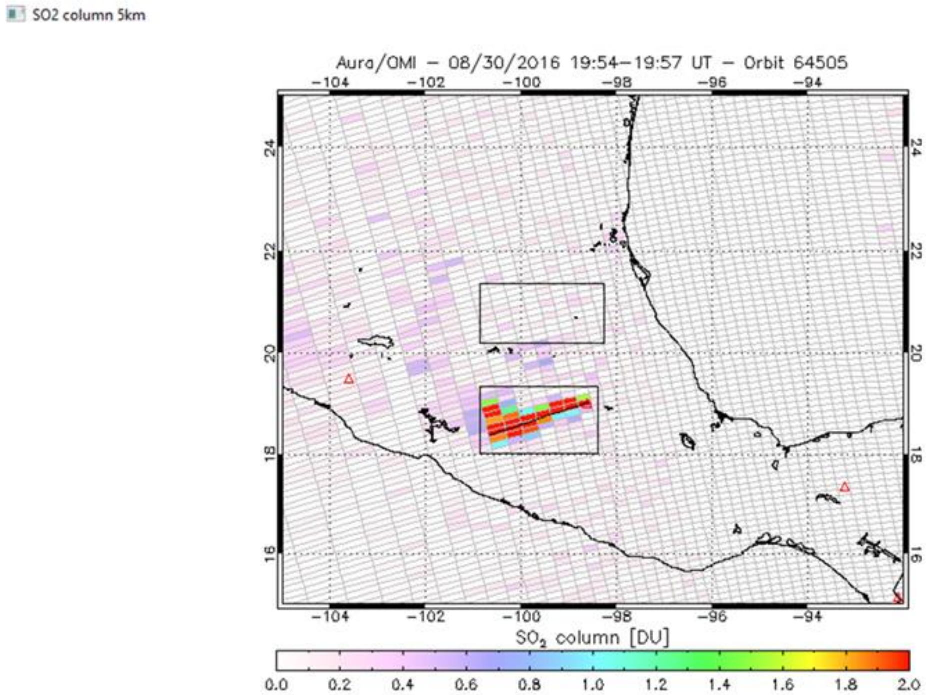

Figure 7. OMI image showing the 5 km vertical profile (TRM) for August 30, 2016.

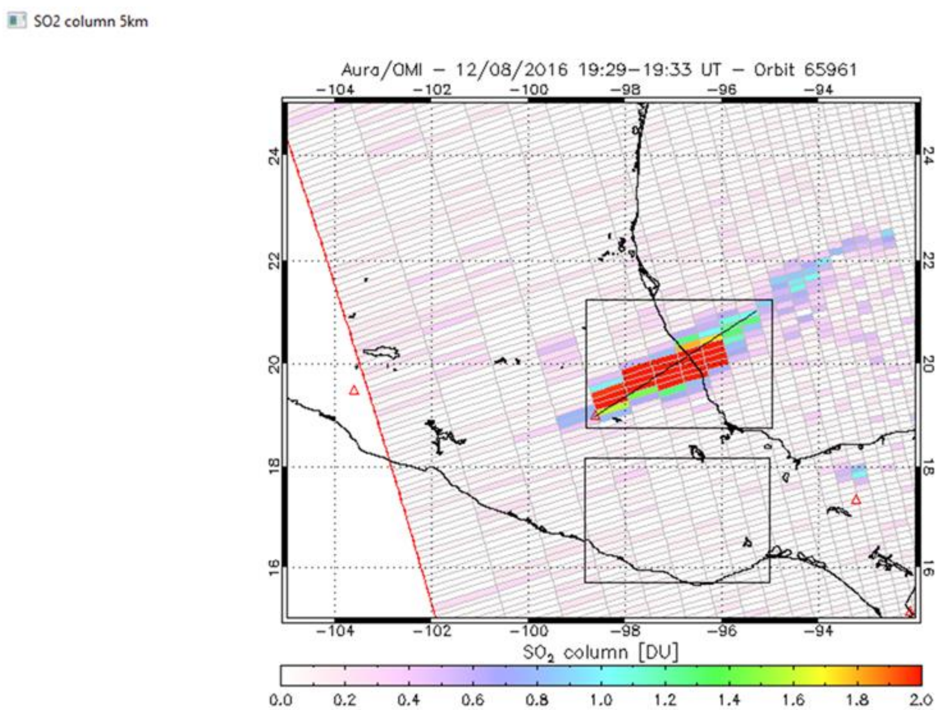

Figure 8. OMI image showing the 5 km vertical profile (TRM) for December 8, 2016.

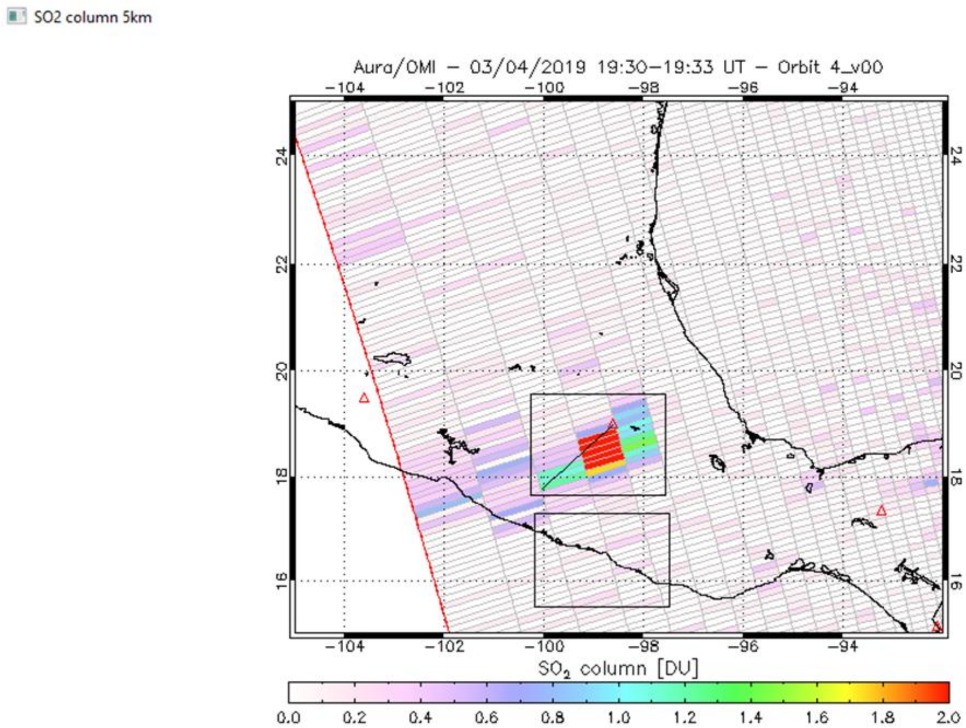

Figure 9. OMI image showing the 5 km vertical profile (TRM) for March 4, 2019.

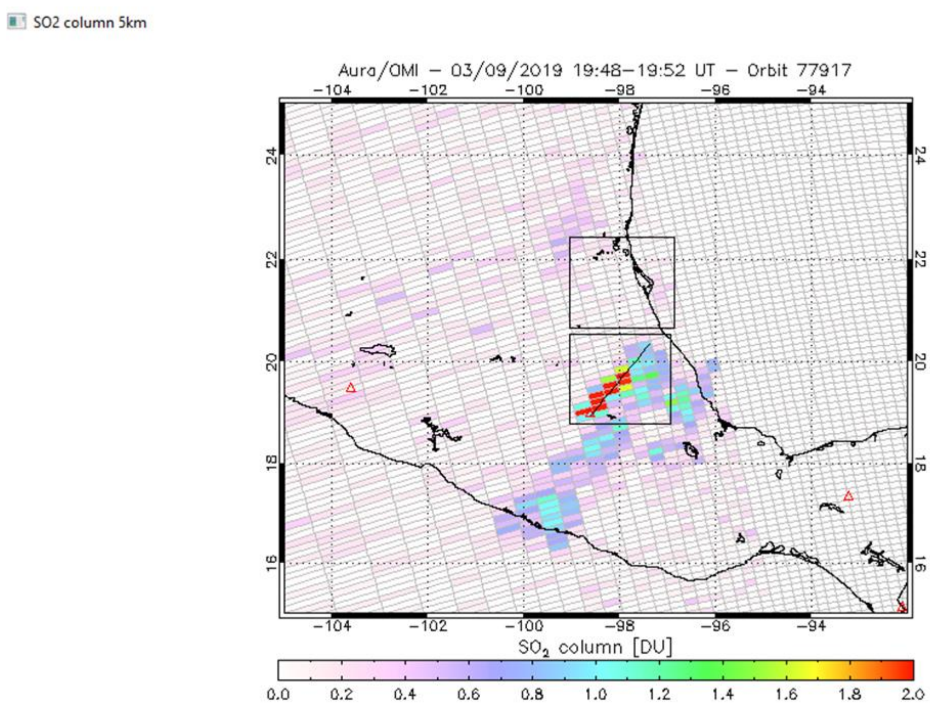

Figure 10. OMI image showing the 5 km vertical profile (TRM) for March 9, 2019.

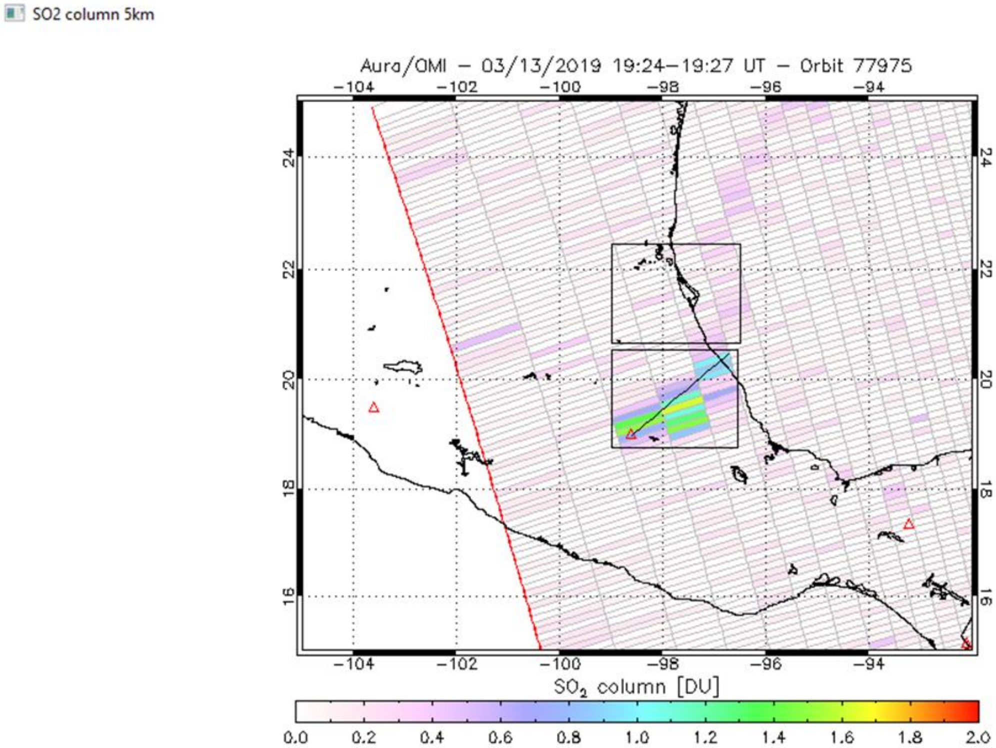

Figure 11. OMI image showing the 5 km vertical profile (TRM) for March 13, 2019.

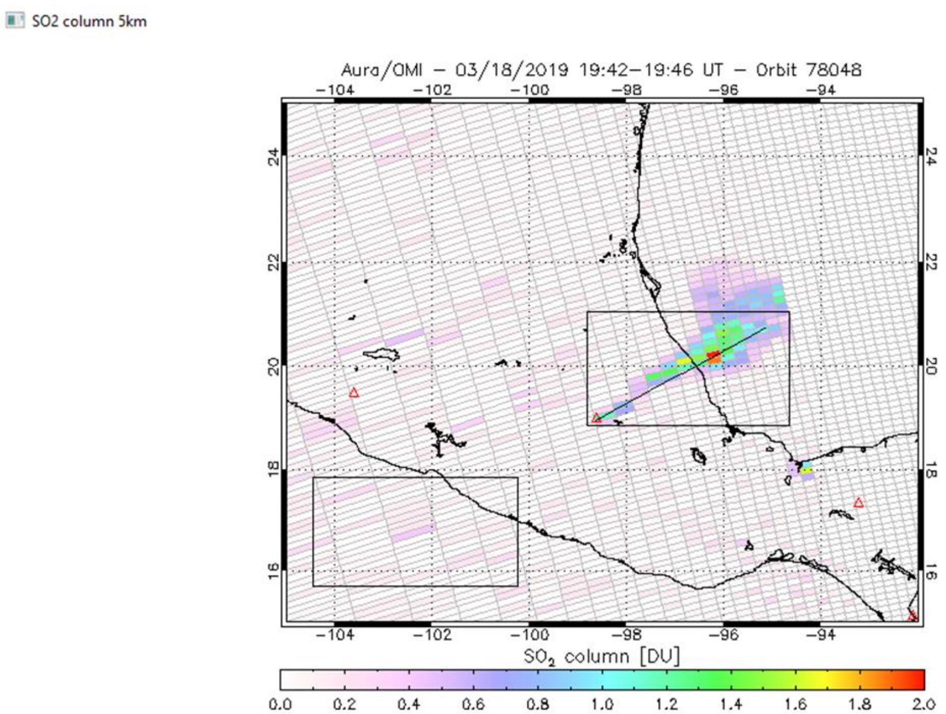

Figure 12. OMI image showing the 5 km vertical profile (TRM) for March 18, 2019.