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Impact of the Popocatepetl's volcanic activity on the air quality of Puebla City, México

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RESUMEN

En este trabajo se reportan mediciones de contaminantes atmosféricos en la ciudad de Puebla, incluyendo las registradas durante el período caracterizado por una intensa actividad del volcán Popocatépetl, entre diciembre de 2000 y enero de 2001. Aplicamos un modelo de dispersión gaussiano para calcular el impacto de las emisiones volcánicas de compuestos de azufre en las mediciones de estos compuestos en las estaciones de la Red de Monitoreo Atmosférico de la ciudad de Puebla. Los datos muestran que durante el período analizado, las emisiones volcánicas afectaron la calidad del aire incrementando los índices de PM_{10}, CO y compuestos de azufre. Además, los resultados del modelo gaussiano de dispersión del aire para los compuestos de azufre, explican las mediciones de la estación Tecnológico para los días con intensa actividad volcánica y viento viniendo del volcán hacia la ciudad de Puebla.

ABSTRACT

In this work we report measurements of atmospheric pollutants in Puebla City, including those registered during the period characterized by intense volcanic activity from Popocatépetl volcano between December 2000 and January 2001. We used a gaussian air dispersion model to calculate the impact of sulfur compounds from volcanic emissions on the measurements of these compounds in the stations belonging to Puebla City

Atmospheric Monitoring Network. The data show that during the analyzed period, this volcanic emissions affected the air quality, increasing the indexes of PM_{10}, CO and sulfur compounds. Also, the results of applying a gaussian air dispersion model to these sulfur compounds explains the measurements from Tecnológico station for days with intense volcanic activity and wind coming from the volcano to Puebla City.

Key words: Volcanic activity, sulfur compounds, atmospheric pollution, gaussian model.

1. Introduction

Volcanic activity results in the emission of air pollutants such as sulfur dioxide (SO_2) and particulate matter below ten micrometers in diameter (PM_{10}), known as criteria air pollutants, as well as H_2S, HCl, HF, and H_2SO_4 (Goff *et al*., 1998; Williams-Jones *et al*., 2000).

The emission of sulfur gases from the Popocatépetl volcano (PV) has been monitored closely on an ongoing basis since the beginning of the activity in December 1994 (Delgado-Granados *et al.* 1997; Andres *et al*. 1998; Delgado-Granados *et al*. 2001; Heiken, 1993).

Within the radius of influence of PV (sixty kilometers approximately), lies the Metropolitan Area of México City, one of the biggest cities in the world. In addition, inside this perimeter there is another important urban zone named Puebla City (Delgado Granados *et al*., 2001; Goff *et al*., 1998), with circa two million inhabitants.

Considering its geographical location, the metropolitan area of Puebla is the most important and nearest to the PV. Due to the Popocatepetl's intense volcanic activity and wind direction, Puebla received ash rain and gaseous emissions during December 2000 - January 2001. According to the Centro Nacional de Prevención de Desastres data (National Center for Disaster Prevention), in 84% of those 62 days, the wind direction was towards the Northeast-East-Southeast from the volcano's crater (CENAPRED, 2002).

Taking into account the above mentioned, it was considered important to determine the impact that the volcanic emissions had over the air quality of Puebla City and calculate the influence of air pollutants as sulfur compunds in the concentrations measured by the Atmospheric Monitoring Network (AMN) of Puebla State´s stations.

2. Measurements

Puebla City is located in a valley surrounded by the volcanoes Popocatépetl, Ixtaccíhuatl and Malinche. The mean altitude of the city is 2179 meters above sea level and it is located between 18° 40' 53" and 19° 13' 48" of North latitude, and 98° 0' 24" and 98° 14' 48" West longitude.

Taking into account the number of residents, Puebla is the fourth most populates city in the country; it has an intense vehicular traffic as well as an important industrial zone in its metropolitan area (Herrera, 2000).

The Atmospheric Monitoring Network of Puebla State, which started working in August 2000, has four stations distributed in Puebla City as shown in Figure 1.

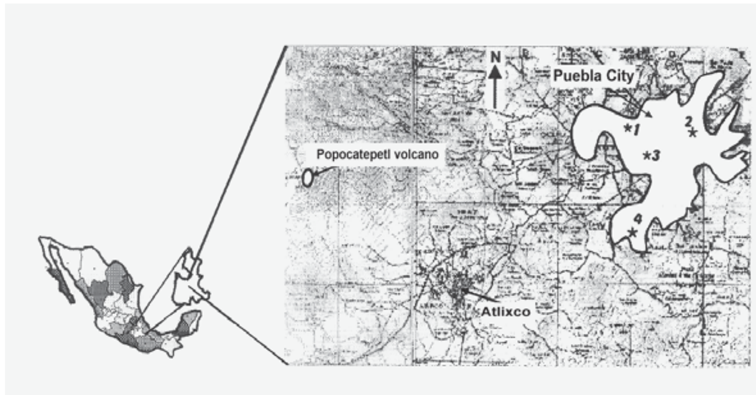

Fig. 1. Schematic map of Puebla City indicating the location of the Atmospheric Monitoring Network stations. 1) Serdán, 2) Tecnológico, 3) Ninfas 4) Agua Santa.

The AMN of Puebla city has devices to analyze gases (Thermo Environmental Instruments), and to measure meteorological parameters (Climatronix) and particles (Andersen); all of which have been certified by the Environmental Protection Agency (EPA) through reference methods and/or equivalents. The AMN provides data about concentrations of criteria air pollutants, H_2S and meteorological parameters.

In Figures 2 to 4, we show the results for some criteria air pollutants in the four stations, for the period from November 2000 to June 2002. In the graphics, the monthly means, maxima, average and the Mexican Official Norm (MON), for each pollutant are shown. The monthly maxima values show the highest levels during periods of volcanic activity indicating its influence on the air quality of Puebla.

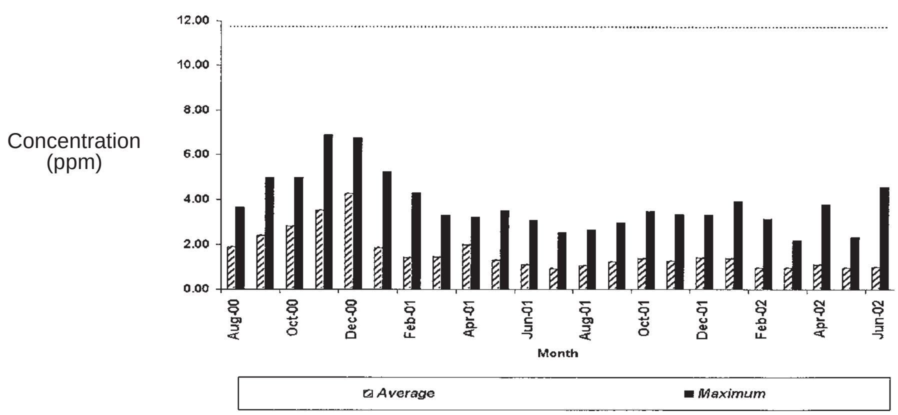

Fig. 2. Concentration of CO during the period August 2000-June 2002 for the four stations of the AMN of Puebla City. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

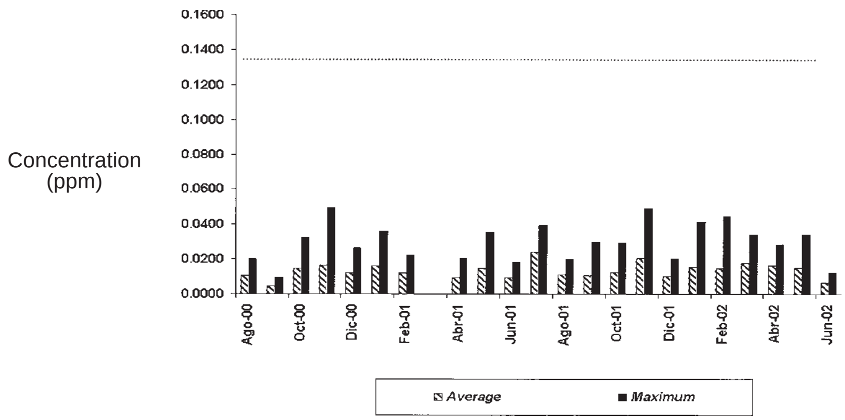

Fig. 3. Concentration of SO_2 for the four stations of the AMN of Puebla City, during the period August 2000-June 2002. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

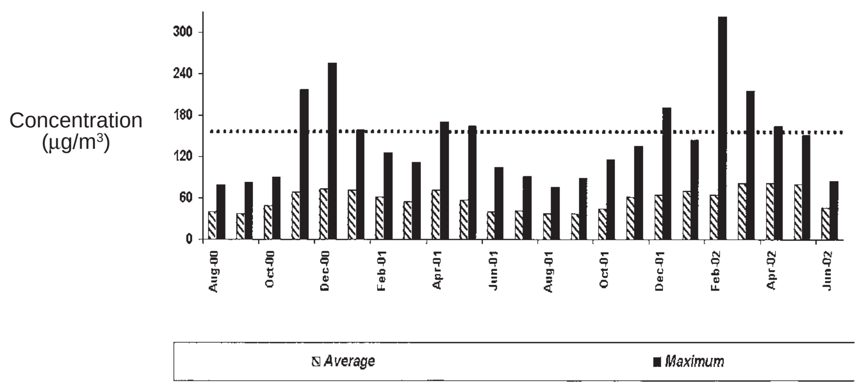

Fig. 4. Concentration of PM_{10} for the four stations of the AMN of Puebla City, during the period August 2000-June 2002. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

Specifically, the daily maxima for the period between December 2000-January 2001 (the period with the maximum PV activity), for the four stations are shown in Figures 5 to 7 for CO, SO_2, and PM_{10}. In all cases, it is clear that the concentrations increased during periods of volcanic activity, reaching values above the norm in certain specific dates.

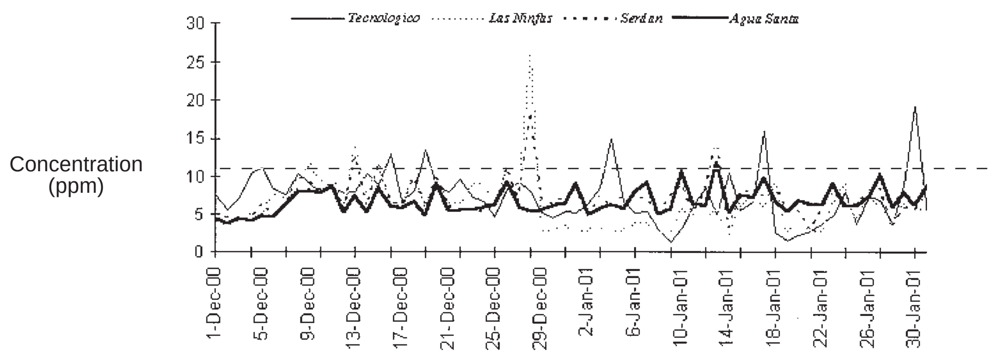

Fig. 5. Daily concentrations of CO for the stations of the AMN of Puebla City, December 2000-January 2001. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

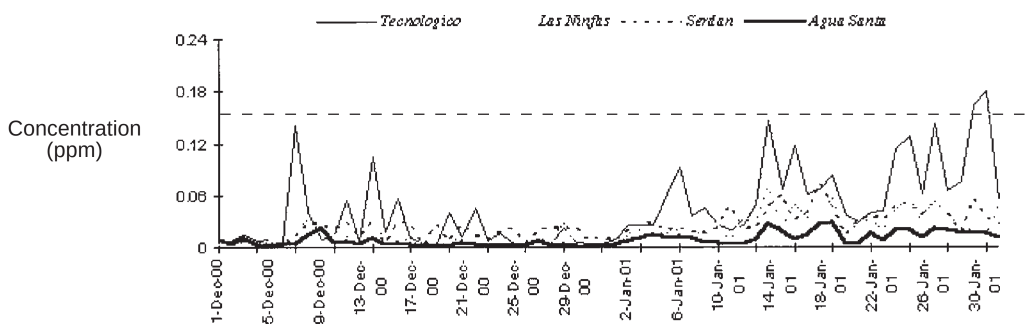

Fig. 6. Daily concentrations of SO_2 for the stations of the AMN of Puebla City, December 2000-January 2001. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

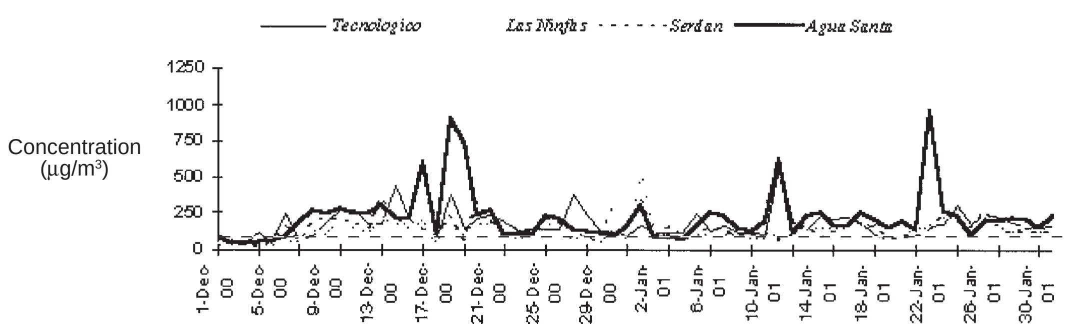

Fig. 7. Daily concentrations of PM_{10} for the stations of the AMN of Puebla City, December 2000-January 2001. The Mexican Official Norm (MON) is represented with the horizontal dashed line.

3. Gauss' diffusion equation applied to the PV emission of sulfur compounds

The gaussian diffusion model (Nevers, 1997; Wark-Warner, 1998) allows us to estimate the concentration of pollutants as a function of the wind direction, considering a source point *X (x, y, z)*. In its general form, the concentration is given by the following equation:

$$c = \frac{Q\Delta t}{8(\pi t)^{3/2}(k_x k_y k_z)^{1/4}} \exp\left[-\left(\frac{1}{4t}\right)\left(\frac{x^2}{k_x}+\frac{y^2}{k_y}+\frac{(z\text{-}H)^2}{k_z}\right)\right], \qquad (1)$$

where c = pollutant's concentration (mass/volume), k = coefficient of turbulent dispersion (area/time), t = dispersion time of the pollutants flow, Q = rate of emitted gases, Dt = duration of the emission, and H = plume's effective height.

The plume's effective height is given by the following relation $H = h + Dh$, where h is the chimney's height (in our case the PV's crater) and Dh is the height that PV's flow reaches, and is calculated using Holland's equation (Wark-Warner, 1998):

$$\Delta h = \frac{V_s\, d}{u}\left[1.5 + 2.68\times10^{-3}\, Pd\left(\frac{T_s - T_a}{T_s}\right)\right], \qquad (2)$$

where V_s = escape speed of the gases from the chimney (m/s), T_s = temperature of the chimney's gas (C°), T_a = environmental temperature (C°), d = diameter of chimney's exit (m), u = wind speed at the chimney's height (m/s) and P = atmospheric pressure (atm).

4. Restrictions when applying the gaussian model

The gaussian model for a point source assumes that the pollutant concentrations in any point are stabilized and do not depend upon time. The pollutants are dispersed in the wind direction and are swept away with the same speed (Nevers, 1997; Wark-Warner, 1998). In order to apply the model, some requirements need to be assumed as following (Perry-Green, 1984; Wark-Warner, 1998):

1. The gas density is higher than that of air.
2. Possible accumulations of other substances are dismissed.
3. The wind speed is higher than 0.5 m/s, which means that there is no turbulence.
4. The location must not suffer the effects due to the evaporations from the sea into the atmosphere.
5. Possible reactions of the gas inside the plume are dismissed.
6. Complex topography is absent, e.g. irregular soils and high elevations surrounding the issuing focus.

In our study, and taking into account the existent conditions for the emissions of the Popocatépetl volcano, all this restrictions were observed.

Applying this model and considering the PV emanations, the concentrations of SO_2 (in mg/m^3) were calculated as a function of the distance from the origin of the source. In this way, and using the parameters shown in Table 1, we obtained the concentrations of the pollutants in the transversal plane as well as in the X direction (where the wind is directed).

Table 1. Parameter used in the calculation of the gaussian dispersion.

Data to calculate the gaussian plume caused by the PV	
Chimney´s height above Puebla Citys´ level (m)	3271
Escape speed of the gases (m/s)	10
Wind speed (m/s)	10
Atmospheric pressure (atm)	0.6
Atmospheric temperature (ºC)	4
Escape temperature of the gases (ºC)	100
Diameter of the chimney (m)	99.4
Rate of emitted gases (g/s)	1419
Atmospheric stability	B

The results for the dispersion of SO_2 obtained using the parameters above, are shown in the following tables. In both cases we have considered a rectangle of 52 km × 42 km and the Northeast wind direction respective to the PV crater. Table 2 presents the view in the XY plane at 2000 m of

Table 2. Concentrations of SO_2 in the X-Y plane, obtained from the application of the gaussian model dispersion.

	Concentration µg/m^3									
	42000	0	0	0	0	0	0	0	0	0
	39092	0	0	0	0	0	0	1	0	0
	36085	0	0	0	0	3	18	38	5	0
	33078	0	0	1	13	90	308	246	11	0
	30071	0	4	22	212	820	1301	408	6	0
	27064	9	61	340	1324	2812	2152	291	2	0
Y	24057	90	444	1659	3993	4777	1874	122	0	0
	21050	512	1808	4569	6941	4869	1049	36	0	0
	18042	1820	4647	8055	7935	3415	432	9	0	0
	15035	4420	8245	9998	6587	1821	144	2	0	0
	12028	7848	10849	9405	4279	794	42	0	0	0
	9021	10765	11205	7105	2303	299	11	0	0	0
	6014	11927	9507	4512	1074	101	3	0	0	0
	Distance (m)	5777	11555	17333	23111	28888	34666	40444	46222	52000
					X					

altitude above surface level. Table 3 presents the concentrations in the XZ plane.

In Table 3, the emission source is situated in the second column (from left to right). This table shows that at 20800 meters from the origin of the source (in the X direction), the pollutants made

Table 3. Concentrations of SO_2 in the Z-X plane, obtained from the application of the gaussian model dispersion.

Concentration µg/m³

	17000	0	0	1	23	78	130	159	168	164	155
	16190	0	0	5	55	100	186	205	203	190	175
	15380	0	0	20	119	214	255	257	240	217	194
	14571	0	1	72	233	323	336	313	278	243	213
	13761	0	10	211	414	459	426	370	315	268	230
	12952	0	82	318	667	616	318	423	350	291	247
	12142	0	525	1057	976	777	605	476	381	311	261
	11333	82	1905	1796	1293	923	679	517	405	327	272
	10523	3821	4422	2539	1555	1034	733	545	422	339	282
Z	9714	23179	6565	2986	1695	1090	739	560	432	346	288
	8904	1873	6232	2923	1676	1082	756	558	432	349	292
	8095	25	3783	2381	1502	1012	723	542	425	347	293
	7285	0	1468	1614	1222	892	664	512	410	340	292
	6476	0	356	910	901	740	587	471	389	331	289
	5666	0	58	427	602	578	499	424	364	320	285
	4857	0	6	167	365	462	410	374	338	307	280
	4047	0	0	54	201	297	327	326	313	295	375
	3238	0	0	15	100	191	256	284	290	284	270
	2428	0	0	3	46	128	203	251	273	276	267
	1619	0	0	1	21	88	170	230	262	270	264
	809	0	0	0	14	75	158	223	258	286	263
	Distance (m)	5200	10400	15600	20800	26000	31200	36400	41600	46800	52000
						X					

contact with the surface, it also shows that the maximum concentration in that level occurred at 46 800 meters.

Also considering Table 3, 52000 meters away from the origin of the source (the distance from which the Tecnológico station is located), there is a concentration of 263 µg/m³. Converting this concentration to parts per million, we obtained the value of 0.09 ppm. We can consider this quantity the contribution of the PV to the measurements for SO_2 at the Tecnológico station.

On the other hand, taking into account the recorded data by the AMN on January 29, 2001, a maximum concentration of 0.18 ppm is found for SO_2 in the Tecnológico station. Application of the gaussian model suggests that the contribution by the PV would be around the 50% of the total concentration that was recorded for that particular day. This is consistent with historical measurements by the AMN during winter season for that station.

Additionally, we estimate the arrival time of the pollutants flow from the PV to the Tecnológico station as 2 hours; emissions from the PV when the wind direction is towards Puebla City rapidly affect the city's air quality.

5. Discussion

According to Figures 2 to 4, the Mexican Official Norm (MON) for the PM_{10} air pollutants has been surpassed for some periods in the four stations located in Puebla City. In those figures, a seasonal behavior is observed for carbon monoxide with important increases during the winter period and with an outstanding value over the winter 2000-2001. During the same periods, PM_{10} had the same behavior.

On the other hand, the PV's volcanic activity during recent years has been characterized by emissions of ash and gases, especially during the months of December and January.

Figure 8 shows the isopleths associated to Table 2.

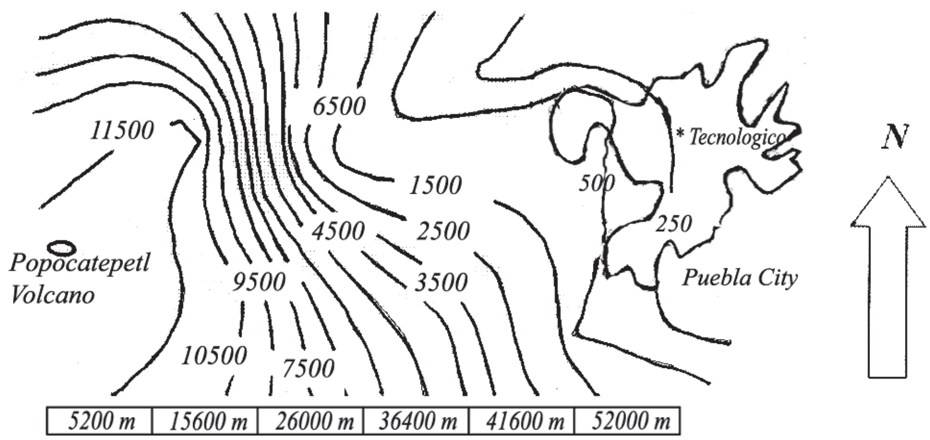

Fig. 8. Isopleths (in µg/m^3) obtained using data in Table 2 after the gaussian model.

The wind rose for the months of December 2000 and January 2001 is shown in Figure 9. In accordance with this figure, for the majority of days for this period, the wind flew in a Northeast-East-Southeast direction, towards the region in which the metropolitan area of Puebla is located.

This behavior explains the fact that during December 2000-January 2001 the concentration of sulfur compounds, PM_{10} and carbon monoxide increased in comparison to a similar period a year later (December 2001-January 2002), as shown in Figures 10-12.

According to Figures 5, 6, 7 and 9, the days when there was intense volcanic activity and the wind blew towards Puebla City, there was a considerable increase in the indexes of pollutants such

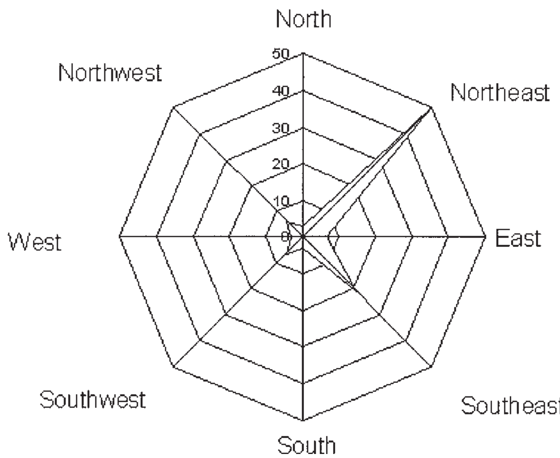

Fig. 9. The wind rose for the PV's crater during the analyzed period. It is appreciated that the Puebla City is located toward the Northeast (considering the PV crater), the wind flew in that direction during the majority of days in that period of time. The numbers on the northern axis represent the average days in which the wind flew toward the specified direction.

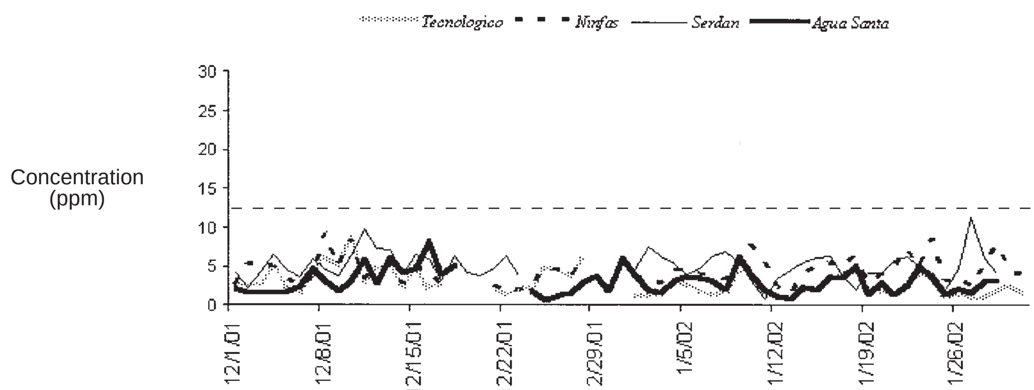

Fig. 10. Daily concentrations of CO for the four stations of the AMN of Puebla City, during the period December 2001-January 2002. The Mexican Official Norm (MON) is represented by a horizontal dashed line. During this period, no weekly measurements were taken.

as PM_{10}, carbon monoxide and sulfur dioxide. This is in line with the hypotheses that volcanic activity affects the air quality of Puebla City.

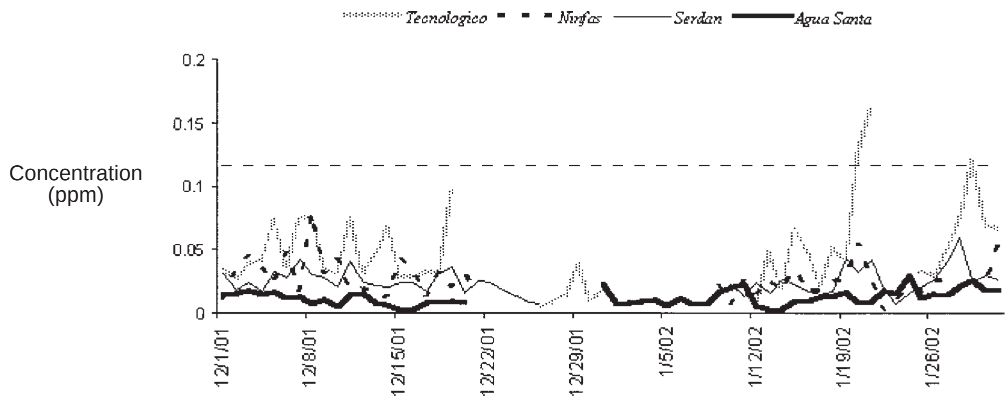

Fig. 11. Daily concentrations of SO_2 for the four stations of the AMN of Puebla City, during the period December 2001-January 2002. The MON is represented by a horizontal dashed line. During this period, no weekly measurements were taken.

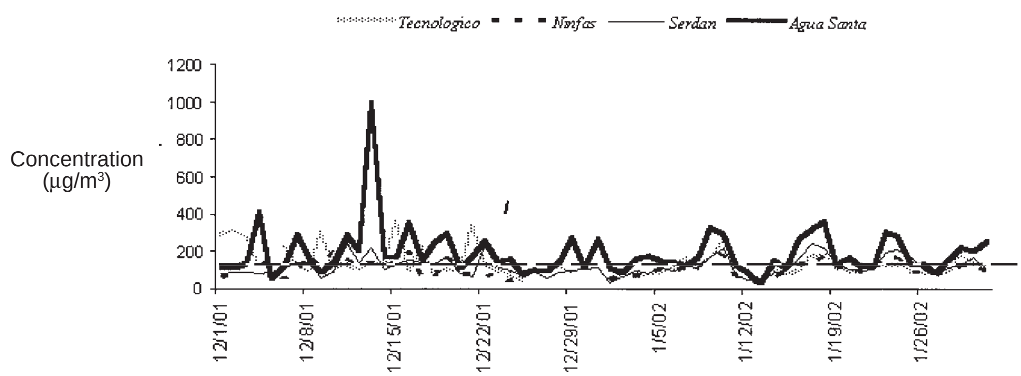

Fig. 12. Daily concentrations of PM_{10} for the four stations of the AMN of Puebla City during the period December 2001-January 2002. The MON is represented by a horizontal dashed line.

An additional supporting argument is found in the Table 4, where the number of times that the MON was exceeded for the different criteria pollutants is shown during both periods, in the four stations of the AMN.

Table 4. Comparison between the number of times that the MON was exceeded during December 2000-January 2001 and December 2001-January 2002.

Number of times (Dec. 2000 - Jan 2001)	Number of times (Dec 2001 - Jan 2002)
(O_3) : 4	(O_3) : 3
(PM_{10}) : 120	(PM_{10}) : 29
(CO) : 15	(CO) : 1
(SO_2) : 7	(SO_2) : 1
NO_2) : no one	(NO_2) : no one

6. Conclusions

According to the analysis, there is a general increase in the concentration of criteria pollutants during volcanic activity, locally affecting Puebla City.

The SO_2 measurements at the Tecnológico station, Figure 6, shows an increase in concentration during the days when the wind direction came from PV. The high concentrations recorded for this pollutant at this station, besides being attributed to the volcanic activity, could also be attributed to the chemical industry established in that zone.

Taking into account the historically measured concentrations at the Tecnológico station for SO_2 and adding the other factors considered in this work, there is congruence with the measured data during days of intense volcanic activity.

In this work we make clear how volcanic emissions influence air quality at Puebla City. Our results show that the pollutants analyzed increased during periods of volcanic activity.

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