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

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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 Popocatepetl 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$_2$S, HCl, HF, and H$_2$SO$_4$ (Goff et al., 1998; Williams-Jones et al., 2000).

The emission of sulfur gases from the Popocatepetl 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 compounds 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 populous 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.
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, \( \text{H}_2\text{S} \) 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.
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, SO₂, and PM₁₀. In all cases, it is clear that the concentrations increased during periods of volcanic activity, reaching values above the norm in certain specific dates.
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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 SO₂ 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 PM₁₀ 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:

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

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):

\[
\Delta h = \frac{V_s d}{u} \left[ 1.5 + 2.68 \times 10^{-3} P d \left( \frac{T_s - T_e}{T_s} \right) \right],
\]

where \( V_s \) = escape speed of the gases from the chimney (m/s), \( T_s \) = temperature of the chimney’s gas (\( ^\circ \)C), \( T_e \) = environmental temperature (\( ^\circ \)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>
<thead>
<tr>
<th>Distance (m)</th>
<th>5777</th>
<th>11555</th>
<th>17333</th>
<th>23111</th>
<th>28888</th>
<th>34666</th>
<th>40444</th>
<th>46222</th>
<th>52000</th>
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<tbody>
<tr>
<td>Concentration µg/m$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>42000</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>308</td>
<td>246</td>
<td>11</td>
<td>0</td>
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<td>212</td>
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<td>1301</td>
<td>408</td>
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<td>61</td>
<td>340</td>
<td>1324</td>
<td>2812</td>
<td>2152</td>
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<td>444</td>
<td>1659</td>
<td>3993</td>
<td>4777</td>
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<tr>
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<td>512</td>
<td>1808</td>
<td>4569</td>
<td>6941</td>
<td>4869</td>
<td>1049</td>
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<tr>
<td>18042</td>
<td>1820</td>
<td>4647</td>
<td>8055</td>
<td>7935</td>
<td>3415</td>
<td>432</td>
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<td>4420</td>
<td>8245</td>
<td>9998</td>
<td>6587</td>
<td>1821</td>
<td>144</td>
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<td>0</td>
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<td>12028</td>
<td>7848</td>
<td>10849</td>
<td>9405</td>
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<td>11205</td>
<td>7105</td>
<td>2303</td>
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<td>0</td>
<td>0</td>
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<td>9507</td>
<td>4512</td>
<td>1074</td>
<td>101</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

| 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 |

Table 1. Parameter used in the calculation of the gaussian dispersion.
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 contact with the surface, it also shows that the maximum concentration in that level occurred at 46800 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 SO₂ 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 SO₂ 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.

Table 3. Concentrations of SO₂ in the Z-X plane, obtained from the application of the gaussian model dispersion.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Concentration µg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>17000</td>
<td>0  0  1  23  78  130 159 168 164 155</td>
</tr>
<tr>
<td>16190</td>
<td>0  0  5  55 100 186 205 203 190 175</td>
</tr>
<tr>
<td>15380</td>
<td>0  0 20 119 214 255 257 240 217 194</td>
</tr>
<tr>
<td>14571</td>
<td>0  1 72 233 323 336 313 278 243 213</td>
</tr>
<tr>
<td>13761</td>
<td>0 10 211 414 459 426 370 315 268 230</td>
</tr>
<tr>
<td>12952</td>
<td>0 82 318 667 616 318 423 350 291 247</td>
</tr>
<tr>
<td>12142</td>
<td>0 525 1057 976 777 605 476 381 311 261</td>
</tr>
<tr>
<td>11333</td>
<td>82 1905 1796 1293 923 679 517 405 327 272</td>
</tr>
<tr>
<td>10523</td>
<td>3821 4422 2539 1555 1034 733 545 422 339 282</td>
</tr>
<tr>
<td>Z 9714</td>
<td>23179 6565 2986 1695 1090 739 560 432 346 288</td>
</tr>
<tr>
<td>8904</td>
<td>1873 6232 2923 1676 1082 756 558 432 349 292</td>
</tr>
<tr>
<td>8095</td>
<td>25 3783 2381 1502 1012 723 542 425 347 293</td>
</tr>
<tr>
<td>7285</td>
<td>0 1468 1614 1222 892 664 512 410 340 292</td>
</tr>
<tr>
<td>6476</td>
<td>0 356 910 901 740 587 471 389 331 289</td>
</tr>
<tr>
<td>5666</td>
<td>0 58 427 602 578 499 424 364 320 285</td>
</tr>
<tr>
<td>4857</td>
<td>0 6 167 365 462 410 374 338 307 280</td>
</tr>
<tr>
<td>4047</td>
<td>0 0 54 201 297 327 326 313 295 275</td>
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<tr>
<td>3238</td>
<td>0 0 15 100 191 256 284 290 284 270</td>
</tr>
<tr>
<td>2428</td>
<td>0 0 3 46 128 203 251 273 276 267</td>
</tr>
<tr>
<td>1619</td>
<td>0 0 1 21 88 170 230 262 270 264</td>
</tr>
<tr>
<td>809</td>
<td>0 0 0 14 75 158 223 258 286 263</td>
</tr>
</tbody>
</table>

→↑

X

→↑

Z
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/m³) obtained using data in Table 2 after the gaussian model.](image)

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
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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.
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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.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>PM₁₀</td>
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<td>29</td>
</tr>
<tr>
<td>CO</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>SO₂</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>NO₂</td>
<td>no one</td>
<td>no one</td>
</tr>
</tbody>
</table>

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 SO₂ 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 SO₂ 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.

References


