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# Determination of the atmospheric optical depth due to the El Chichon stratospheric aerosol cloud in the polluted atmosphere of Mexico City

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RESUMEN

Se utilizaron mediciones de radiación solar directa para determinar el incremento de la profundidad óptica del aerosol (AOD) asociada a la presencia de aerosoles y partículas grandes (cenizas) originadas por las erupciones de El Chichón (17.5°N, 93.3°W; México) del 28 de marzo al 4 de abril de 1982 sobre la capa atmosférica contaminada de la Ciudad de México. Los resultados se comparan con los obtenidos en Vancouver, Colombia Británica, revelando que un primer aumento de AOD ocurrió en ambos lugares durante mayo, junio y julio de 1982. Sin embargo, la AOD decayó en Ciudad de México más lentamente, alcanzando los valores climatológicos normales hasta febrero de 1983. Mientras tanto la AOD para Vancouver alcanzó valores mínimos en septiembre de 1982; éstos subsecuentemente se incrementaron en el período de octubre de 1982 hasta septiembre de 1983. Este máximo secundario se registró en la Ciudad de México de marzo a agosto de 1983. Los resultados sugieren que los primeros aumentos de AOD en mayo, junio y julio de 1982, tanto en Vancouver como Ciudad de México, se deben principalmente a partículas grandes de ceniza, de vida media corta, suspendidas en la baja atmósfera. Sin embargo, el segundo incremento de AOD, asociado con atardeceres anormalmente coloreados, corresponde a aerosoles volcánicos estratosféricos.

ABSTRACT

Direct solar radiation measurements were used to determine the aerosol optical depth (AOD) increase associated with the presence of aerosol and large particles (ash) originating from the 28 March to 4 April 1982 El Chichón eruptions (17.5°N, 93.3°W; Mexico) on Mexico City's polluted atmospheric aerosol layer. The results are compared with those obtained at Vancouver, British Columbia, revealing that a first AOD increase occurred in both locations during May, June, and July 1982. However, the Mexico City AOD decay is more extended, not reaching normal climatological values until February 1983. Meanwhile, Vancouver's AOD reached minimum values in September 1982, which subsequently increased over a period from October 1982 to September 1983. This secondary maximum was recorded in Mexico City from March to August 1983. Results suggest that the first AOD increases in May, June and July 1982, both at Vancouver and Mexico City, are due chiefly to short life-time volcanic ash particles being located near the surface. However, the second AOD increases, associated with anomalously colored twilights, corresponds to stratospheric volcanic aerosols.

## 1. Introduction

Climate and its global change, due to both natural and anthropogenic causes associated with atmospheric aerosols, is an important aspect which requires further study (Galindo, 1992; Jennings, 1993; Kondratyev and Cracknell, 1994; Newell, 1984). Atmospheric aerosols interact both with incoming short-wave radiation and emitted long-wave thermal radiation. These interactions produce a redistribution of short-wave solar radiation and infrared thermal emission due to scattering and absorption by non-uniformly distributed atmospheric aerosol particles, which greatly affect the surface-atmosphere system radiation budget. Near the surface, industrial emissions represent the greatest contributors to tropospheric $H_2SO_4$- -aerosol, producing mass quantities of so-called atmospheric pollution. On the other hand, stratospheric aerosols are primarily formed by the sporadic injection of sulfuric acid aerosol originating from volcanic eruptions. Numerical modeling studies of tropospheric aerosol reveals that the Northern Hemisphere's principal global sulphur compound sources are: 64 TgS/yr from industries, 6.9 TgS/yr from the oceans, and 5.8 TgS/yr from volcanoes, respectively (Langner and Rodhe, 1991). In other words, these three factors contribute approximately 78, 11 and 9 percent, respectively, of total tropospheric sulphur compounds. Consequently, distinguishing the volcanic signal, which provides a much smaller (10x) set of distinguishable measurements from the more vigorous anthropogenic signal, represents a most difficult task.

Aerosol physical properties, which include size, shape, refractive index and atmospheric concentration, control aerosol interaction with the radiation field, according to a set of derived parameters which are otherwise known as optical properties. One of the basic optical properties which can be obtained from radiation measurements, is aerosol optical depth, which is a measurement of particle size and number present within a given column of air (Kondratyev, 1988).

This paper reviews aerosol optical depth findings for both tropospheric (industrial) and stratospheric (volcanic) aerosols which were registered over Mexico City before, during and after the El Chichón (17.5° N, 93.3° W) volcanic eruptions.

## 2. The El Chichón eruptions

On 28 March 1982, at 23:30 local time (LT), the El Chichón volcano, located in Mexico's southeastern state of Chiapas, began its eruptive activity. El Chichón underwent three major eruptions between late March and early April 1982. This late Pliocene or early Pleistocene volcano is located at the eastern extreme of the Mexican Neovolcanic Belt, on the current Chiapas volcanic arc. During historical times, this volcano has exclusively exhibited solfataric activity. Because the region of Chiapas is located at the junction of the American, Cocos, and Caribbean tectonic plates, volcanic activity is believed to be due, in large part, to continuous subduction of the Cocos plate beneath the southeastern part of Mexico.

As has been pointed out by Hofmann (1987) and Hofmann and Rosen (1987), more has been learned about volcanic aerosol effects on the stratosphere following the El Chichón eruption than from all previous eruptions combined. This was principally due to great number and variety of experienced researchers, technologies and research techniques that were immediately brought to the scene. For the first time, researchers found that trace chemical species such as HCl and OH increased following the eruption. Interestingly, and possibly related to HCl and OH increases, were reduced post- eruption concentrations $O_3$, NO, and $NO_2$.

The presence of volcanic $SO_2$ was confirmed for the first time, using satellite observations. Furthermore, its subsequent reactions which convert $SO_2$ into vapour $SO_3$, condensation nuclei

and, finally, sulphuric acid aerosol were also closely monitored by both *in situ* and remote sensing techniques.

At present, it appears that at least three primary factors contributed to the severity of the eruption. These factors include the apparently large proportion of sulphur involved in this moderate-size eruption, the latitude of the volcano and the time of year of the eruption. The final eruption, on 4 April, reached altitudes in excess of 25 km and probably injected more sulphurous gases into the atmosphere than any other eruption registered during the previous 100 years (Kondratyev and Galindo, 1995). Total erupted $SO_2$, provided by TOMS data, gave 3.3 Mt. Results reveal that $SO_2$ chemical conversion into $H_2SO_4$ has a life-time of approximately one month rather than a year as previously thought. This conclusion has been subsequently confirmed by balloon data analyses.

The first eruption's initial product was tephra, enriched with a crystalline component and accompanied by large amounts of silicon alkalines, as compared to pyroclastic matter of the second and third eruptions. The initial tephra also consisted principally of juvenile substances, which were subsequently followed by eruptive products primarily composed of both juvenile and lithoid fractions. The first eruptions were characterized by large amounts of ejected ash, moderate amounts of pumice and smaller amounts of lithoid fragments. During the first phase of the eruption which continued until 2 April, large amounts of light-gray ash were ejected, covering the adjacent area northeast of the volcano. The deposited ash layer reached thicknesses of 0.5 m at a distance of 15 km and decreased to 0.2 m at a distance of 75 km from the volcano. The ash layer in Villahermosa, capital of the adjacent state of Tabasco, was approximately 0.1 m thick.

The second phase consisted of two large-scale eruptions (3 April, 19:33 LT; 4 April, 05:36 LT), which produced brown-gray ash with a large percentage of lithic tephra which was ejected and propagated, for the most part, to the east of the volcano. On 4 April, at 10:30 LT, the rate of settling for ash near Teapa reached 0.33 $g/m^2s$, which immersed this region in nearly total darkness, reducing visibility to 5 m. By 12:30 LT the rate of settling decreased by 0.05 $g/m^2s$. On this day, pyroclastic streams consisting of hot ash and large blocks of pumice, moved down the slopes of El Chichón. The tephra layer thickness, measured on 5 April near Palenque, a city approximately 125 km east of El Chichón, exceeded 0.4 m.

Chemical analyses of 30 samples collected at different locations between April 3 and 7 revealed two types of tephra:

i) Light gray matter with a high percentage of silicon (59% average) was ejected between 28 March and 2 April. This matter was subsequently covered by tephra containing large amounts of lithic components (the April 3 and 4 eruptions).

ii) Basaltic tephra with a high percentage of iron, magnesium and calcium oxides.

As Robock (1983) noted, the stratospheric post-El Chichón 4 April 1992, eruptive cloud was apparently the most powerful cloud (up to that time) recorded this century. This cloud caused a local temperature decrease of more than 5° C and a further cooling of up to 0.5° C was expected near the surface in 1984-1985.

The interpretation of data from a unique combination of complex post-eruption ground-based balloon, aircraft and satellite observations made the verification of gas-to-particle conversion models, as a source of stratospheric $H_2SO_4$ aerosol, possible. This combination also calculated particle transport, gravitational setteing and aerosol impact on the radiative regime and climate.

The El Chichón eruptive cloud circled the Earth for 21 days at an average speed of 22 m/s (Robock, 1984). Lidar soundings, registered in Hawaii, over which the thickest part of the

cloud passed on 9 April, provided backscattering coefficient values (determined with respect to Rayleigh scattering) exceeding 200, which had never previously been observed, with a maximum at the 26 km-level (DeLuisi *et al.*, 1983). The eruptive cloud also proved to be stratified. Two months after the eruption, the upper layer, with a maximum concentration at a height of 20 km, apparently propagated over the entire globe. Therefore, simultaneous aerosol optical depth comparisons from two distant places, such as Vancouver and Mexico City, can provide significant insight as to subsequent volcanic aerosol evolution.

## 3. Determination of aerosol optical depth (AOD)

Aerosol optical depth is the sum of aerosol absorption and scattering coefficients integrated over the entire atmospheric depth. It is an appropriate variable for studies related to anthropogenic and volcanic aerosol effects. Unlike other variables such as the bulk atmospheric transmittance, AOD is independent of solar angle and the concentration of other atmospheric constituents such as water vapour and ozone. Therefore, it can be used to compare the attenuation of direct solar radiation over all time scales for which data are available (Hay and Darby, 1984).

The approach used to calculate AOD is based on the work of Davies and Hay (1980), which has subsequently been adopted by Freund (1983) and Hay and Darby (1984). These studies provide the basis for the particular empirical relationships used in the present investigation. The basic equation is:

$$\tau_a = 1/\{m' \ln[I/(T_o T_r - a_w) I_o]\} \tag{1}$$

where

$\tau_a$ = aerosol optical depth [dimensionless or atmosphere$^{-1}$]
$m'$ = pressure corrected optical air mass [dimensionless]
$I$ = direct radiation at normal incidence [MJm$^{-2}$h$^{-1}$]
$T_o$ = transmittance after ozone absorption [dimensionless]
$T_r$ = transmittance after Rayleigh scattering [dimensionless]
$a_w$ = water vapour absorptance [dimensionless]
$I_o$ = solar radiation flux density outside the atmosphere [MJm$^{-2}$h$^{-1}$].

The optical air mass (m) is calculated using the formula presented by Kasten (1966):

$$m = 1/[\cos z + 0.15\ (93.885 - z)^{-1.253}] \tag{2}$$

where $z$ is the solar zenith angle in degrees. The corrected optical air mass incorporates actual station pressure (p in kPa) such that

$$m' = mp/101.3. \tag{3}$$

Ozone attenuation is calculated using empirical formulae of Lacis and Hansen (1974). The relevant equations are:

$$T_o = 1.0 - a_{vis} - a_{uv} \tag{4}$$

$$a_{vis} = 0.002118X/(1.0 + 0.0042X + 0.00000323X^2) \tag{5}$$

$$a_{uv} = 0.1082X/(1.0 + 13.86X)^{0.805} + 0.00658X/[1.0 + (10.36X)^3]. \quad (6)$$

The ozone amount is taken to be 3.5 mm (McClatchey *et al.*, 1971). This gives an air mass corrected value (X) in mm defined by:

$$X = 3.5m'. \quad (7)$$

Again following Lacis and Hansen (1974), the water vapour absorptance is determined using:

$$a_w = 2.9w'/[(1.0 + 141.5w')^{0.635} + 5.925w'] \quad (8)$$

where

$$w' = mw(p/1013.25)^{0.75}. \quad (9)$$

The precipitable water (w), in mm, is estimated using the equation suggested by Won (1977):

$$w = 0.1 \exp\,(2.2572 + 0.05454T_d) \quad (10)$$

where

$$T_d = \text{Dew point temperature}[^\circ C].$$

To calculate the dew-point temperature, the following empirical relationship (Estrada and Arroyo, 1988) was used:

$$T_d = 1.0/[T - log\,(RH - 2.0)/2352.6] \quad (11)$$

where

$$T = \text{ambient temperature [K] and RH} = \text{relative humidity}[\%].$$

The analysis of atmospheric pressure over a one year period indicates that pressure variation is negligible. Subsequently, the following approximations are used:

$$a_{vis} = 0.0020279X + 0.00023211 \quad (12)$$

$$a_{uv} = 0.00070438X + 0.0141164. \quad (13)$$

Similarly, precipitable water $w$ is obtained in terms of RH and $T_d$, following Iqbal (1983):

$$w = 0.493RH/[T_d \exp(26.23 - 5416/T_d)] \quad (14)$$

Finally, the Rayleigh transmittance term ($T_r$) is obtained using a polynomial fitted to the data according to Davies and Hay (1980):

$$T_r = 0.98552 - 0.10345m' + 0.01733m'^{2} + 0.00198m'^{3} + 0.00011m'^{4} - 0.000002m'^{5} \quad (15)$$

Thus $AOD = AOD(I, m, p, T_d)$.

An assessment of calculated AOD sensitivity to errors associated with input data and empirical relationships, gives probable AOD uncertainty of less than 0.72% with respect to the method proposed by Hay and Darby (1984). Therefore, the results obtained at Mexico City are comparable to those obtained by these authors at Vancouver, B.C.

## 4. The data

The hourly direct solar radiation clear-sky data were obtained from measurements performed with a calibrated Linke and Feussner pyrheliometer at the Solar Radiation Observatory, located on the National University campus in Mexico City. These readings were consistently taken between 10 and 14 hours LT. Hourly meteorological data were also obtained from the Centro de Ciencias de la Atmósfera station, located at the same site.

## 5. Local AOD climatology

To assess the effects of the El Chichón aerosol cloud, it is necessary to describe local aerosol climatology (Hay and Darby, 1984). Although on campus, *in situ* solar radiation measurements have been made since 1957 (Galindo, 1984), local aerosol climatology presented in this paper is based on 5 years of data prior to the eruption (1977-1981). Figure 1 shows evident AOD seasonal variability, where means for each month of the 5-year record are presented together with extreme values for 1984 and 1985 taken as reference. Although the maximum and minimum AODs occur in May and March, respectively, they are strongly related to synoptic conditions. May, for example, has established rain patterns, while March occurs during the dry season.

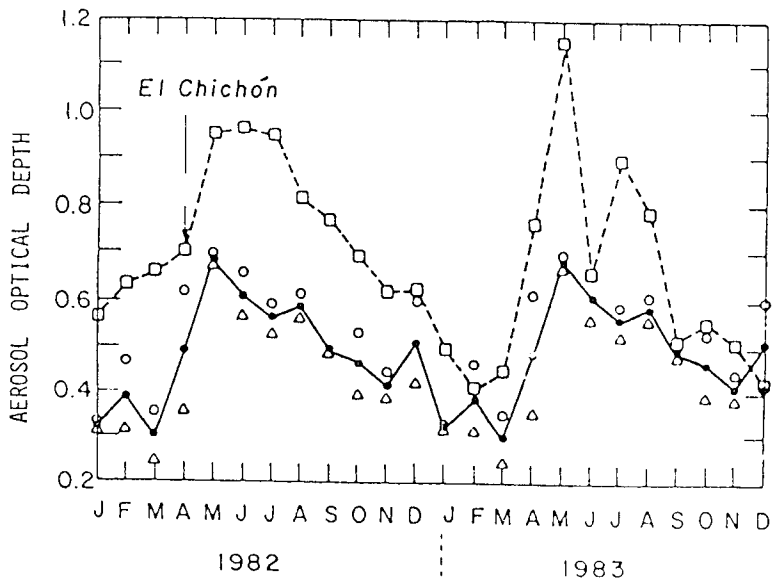


Fig. 1. Aerosol optical depths at México City for 1982 and 1983, and the monthly mean aerosol optical depths (and absolute maximum (o) and minimum (Δ) values) for the five years prior to the eruption of El Chichón.

## 6. Volcanic eruption effects on Mexico City's AOD

At least two volcanic eruptions had the potential to influence Mexico City's radiative conditions over the five-year period studied. The first volcanic event was the eruption of Nyamaragira (1.25°S, 29.12°E) in Zaire, which is considered a major contributor to a subsequent "mysterious" volcanic cloud (Kondratyev and Galindo, 1995). The data presented in Figure 1, show that there is an AOD increase from normal levels during January, February and March 1982, which are probably related to the Nyamaragira event.

As has been previously mentioned, El Chichón underwent four eruptive events from 28 March to 4 April 1982. The last one proved to be the strongest as it reached 25-kilometer heights in the stratosphere. As a consequence, it is expected to have reduced the Northern Hemisphere's atmospheric transparency from the Equator to 40°N. Results shown in Figure 1 indicate that AOD increases steadily continued in April 1982, reaching maximum values during May, June and July 1982. A continuous decay of AOD signals is observed after July, reaching background values in February 1983. A second AOD increase began in March 1983 continuing until it reached its maximum in May 1983. This trend was interrupted in June, when AOD reached climatological values. However, it increased again in July and August 1983, decaying by the end of that year.

The observed El Chichón-induced AOD increases in Vancouver, B.C., as has been reported by Hay and Darby (1984), reveal that AOD increases began to manifest themselves in April 1982. A first maximum set of values is recorded during May, June and July, which slowly decay until September 1982. A second much more powerful AOD increase is exhibited in October 1982, and is sustained until July 1983. Shortly thereafter, AOD tends to decrease, reaching background levels by the end of the year.

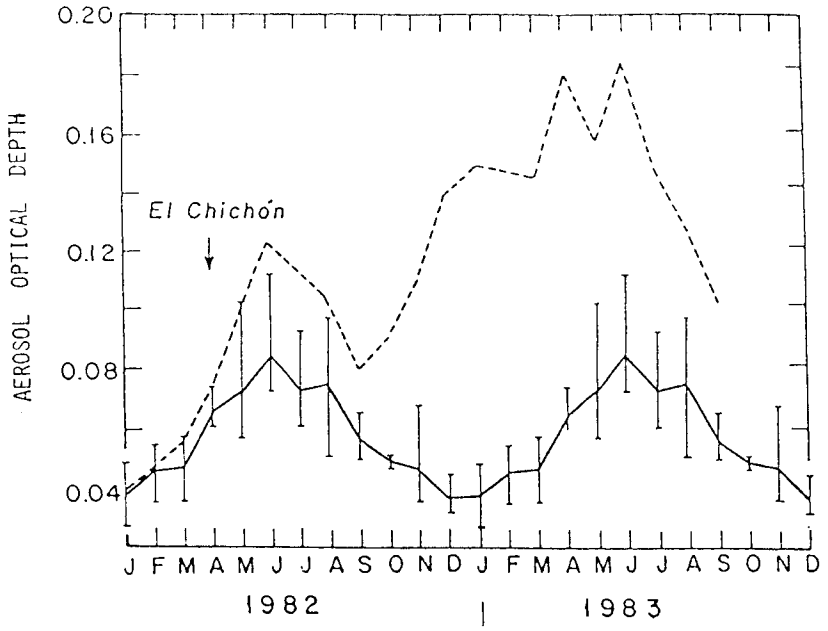


Fig. 2. Aerosol optical depths at Vancouver for 1982 and 1983, and the monthly mean aerosol optical depths (and absolute maximum and minimum values) for the five years prior to the eruption of El Chichón (Hay and Darby, 1984).

Therefore, one can consider that, for both Vancouver and Mexico City, there was an immediate, although brief, AOD response after the El Chichón eruptions. This response was present from May to July 1982. We attribute this AOD increase to relatively large ash particles, composed primarily of $SiO_2$ and pumice (Patterson *et al.*, 1983), rather than volcanically generated $SO_2$ stratospheric acid aerosols. The second volcanic AOD signal seems to be different at both places. The signal had a shorter duration in Mexico City, lasting from March to September 1983, while the Vancouver signal persisted from October 1982 to August 1983. We associate the second AOD increase to El Chichón stratospheric aerosols since these have been associated with colored twilights. In fact, Galindo (1994), using the bulk extinction coefficient method, found a similar short-time two month AOD increase from February to March 1913, which is probably attributable to the 20 January 1913 Volcán de Fuego de Colima (Mexico, 19.5°N, 103.4°W) eruption. On the other hand, after the Fuego (Guatemala, 14.5°N, 91°W) eruptions between 13 and 23 October 1974, increases of the B Schüepp's turbidity coefficient were determined for Mexico City from November 1974 to March 1975. These empirical findings coincided with daily twilights that were witnessed over the city. (Galindo and Bravo, 1975). The association of twilights and increased turbidity coefficient indicate that aerosol, responsible for both processes, is of stratospheric origin.

The AOD increases for Mexico City, due to the El Chichón eruptions, seem to be in phase with the seasonal cycle. This may be because the quasi - biennial oscillation was at its maximum easterly phase with stratospheric winds from the east at about 25 m/sec in the 10°N and 10°S latitudinal belt (Matson and Robock, 1984). Mexico City AOD increases indicate direct solar radiation reductions of up to 30%, while for Vancouver they reached 33% (Hay and Darby, 1984). Detailed radiation measurements of 13 independent radiative fluxes at Fairbanks, Alaska (64° 49' N, 147° 52' W) from 1 July 1979 to 30 June 1984 showed that the El Chichón volcanic cloud had a major impact on the surface radiative regime with maxima observed in the winter of 1982/83, approximately 9 months after the eruption. Furthermore, direct solar radiation was reduced by as much as 38%. These values show that the volcanic cloud was a strong forward scatterer and that relatively little energy was absorbed or reflected back to space (Wendler and Kodama, 1986)

## 7. Conclusions

1. Increases of atmospheric optical depths were observed in both Vancouver and Mexico City from May to July 1982. This AOD increase can principally be ascribed to short life-time large ash particles rather than to stratospheric enhanced acid aerosol. The AOD decay in Vancouver and Mexico City lasted until September 1992 and February 1993, respectively, demonstrating the slow decay which occurred in both places.

2. A second AOD increase was observed in Vancouver from October 1982 to September 1983. For Mexico City, the second AOD increase was of shorter duration, extending from March to September 1983. Acid stratospheric aerosols are considered responsible for AOD increases in both cities because colored twilights coincide with the El Chichón eruptions.

3. The time variation of AOD increases for Mexico City seems to be associated primarily with seasonal variations than those for Vancouver. Seasonal variations for Mexico City are perhaps due to the maximum easterly phase of the quasi-biennial oscillation, which is characterized by stratospheric easterly winds between 10°N and 10°S.

4. The El Chichón volcanic cloud had a major impact on the surface radiative regime, with the maximum observed during the winter of 1982/1983, approximately 9 months after the eruptions. Direct solar radiation was reduced by as much as 38% in Alaska, 33% in Vancouver and 30% in

Mexico City. It appears as though the impact of volcanic stratospheric aerosols on short-wave radiation intensity is more pronounced at higher latitudes.

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