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ATMOSPHERIC IMPACT OF THE VOLCANIC ERUPTIONS OF EL CHICHON OVER MEXICO

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RESUMEN

En el presente trabajo reportamos los efectos observados en la troposfera sobre el territorio mexicano después de las erupciones del volcán Chichón. En el estudio se utilizaron los registros de temperatura del aire de cinco observatorios, así como las observaciones de radiación solar y turbiedad atmosférica realizadas en la Ciudad de México.

Los resultados, a partir de los datos observacionales, muestran que de mayo-junio 1982 a marzo-abril 1983 se observó en todos los observatorios una tendencia al enfriamiento de la temperatura en superficie. Al final del enfriamiento, se presentó un calentamiento abrupto en el verano de 1983 concomitante a una extinción importante de la radiación solar directa y la correspondiente elevación de la turbiedad del aire. El enfriamiento regional observado está de acuerdo con los resultados de los modelos sobre efectos atmosféricos de erupciones volcánicas, basados en la transferencia radiativa. Al analizar conjuntamente nuestros resultados con aquellos logrados mediante aviones de reconocimiento de la NASA y los sondeos de globos estratosféricos efectuados durante el mismo período, se llega a la conclusión de que este calentamiento regional, asociado a una importante extinción de la radiación solar, podría deberse al descenso masivo a la troposfera de los aerosoles volcánicos estratosféricos.

ABSTRACT

In the present study we report the tropospheric effects observed on the Mexican territory of El Chichón volcano eruptions. We have used in the study, the air surface temperature records of five observatories as well as solar radiation and atmospheric turbidity measurements made in Mexico City. The results show that from May-June 1982 to March-April 1983, a temperature cooling trend was observed in all the Observatories, followed by an abrupt warming in the summer of 1983 concomitant to an important extinction of direct solar radiation and the corresponding elevation of atmospheric turbidity. The observed regional cooling is in agreement with the results of radiative transfer models on atmospheric effects of volcanic eruptions. The joint analysis of our results together with those reported from NASA aircraft observations and those of stratospheric balloons performed at the same time period, points out to the conclusion that this regional tropospheric warming associated to an important solar radiation extinction, may be due to the massive descent into the troposphere of the stratospheric volcanic aerosols.

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INTRODUCTION

During the eruptive process of the Mexican volcano El Chichón (17.3°N, 93.2°W), between March 28 and April 4, 1982, large amounts of volcanic materials were injected into the stratosphere: about 10^7 metric tons of sulfuric acid soon developed in the stratosphere (Hofmann and Rosen, 1983a; McCormick and Swissler, 1983).

The injection of sulfuric gases and particles into the stratosphere, their latitudinal and longitudinal propagation and the formation of the volcanic aerosol layers, were followed by active and satellite-borne remote sensors (Bandeen and Fraser, 1982).

The Geostationary Operational Environmental Satellite (GOES) was the first satellite that recorded the eruptions. After the first eruption the cloud spread both NE and SW. Due to the tropospheric westerly drift a relative low-altitude aerosol cloud reached soon Cuba (Mojena and García, 1984), however, it was a second component which reached the stratosphere and propagated both to Central Mexico and the Pacific Ocean coasts. This stratospheric component drifted westward encircling the earth in about three weeks (Robock and Matson, 1983). Although the dust cloud appeared to stretch out in longitude it exhibited very little latitudinal motion, remaining several months in the latitudinal band from 10°S to 30°N (Matson and Robock, 1984).

The above important fact was later corroborated by lidar remote measurements carried out by several aircraft missions covering latitudes from 90°N to 56°S (McCormick *et al*, 1984). Through the use of balloon borne optical particle counters, it was also possible to study the formation of two stratospheric aerosol layers, one of very large droplets (main mode radius 0.3 μm) at 25 km and a larger one of nearly the same concentration but of lesser size (main mode radius 0.15 μm) at about 18 km (Hofmann and Rosen, 1983b). Due to the optical properties of such volcanic sulfuric aerosol layers, there was a substantial solar radiation absorption in the tropical stratosphere. This gave place to important stratospheric warmings, during the summer and autumn of 1982, at the 50 and 30-mb levels between 10°S and 30°N (Labitzke *et al.*, 1983, and Quiroz, 1983a).

In the present study we report the observed effects due to the longterm permanence of the stratospheric sulfur-rich aerosol layer on the Mexican territory. We have studied the air surface temperature departures from normals as well as the behaviour in time of the observed changes in the incoming solar radiation and atmospheric turbidity.

DATA

Surface temperatures recorded at five observatories of the Mexican National Meteorological Service, from 1962 to 1983, were used in the present study. Monthly mean temperatures over the period 1962-1981 were computed and used as monthly "normals". The considered observatories, their monthly normals ($\overline{X}_i$) and corresponding standard deviations (σ_i) are given in Table 1.

TABLE 1

Surface Temperature Data:
Monthly Normals and Standard Deviations
(in °C) (Means: January 1962-December 1981)

OBS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ENS	13.8	14.1	14.2	15.6	16.8	18.3	20.3	21.6	20.9	18.8	16.3	14.3
	1.49	1.43	1.38	1.36	1.40	1.66	1.36	1.48	1.59	1.50	1.40	1.43
MER	23.0	23.5	26.2	27.9	28.9	28.2	27.6	27.6	26.8	25.9	24.2	23.1
	1.23	1.11	1.20	1.00	1.06	1.02	0.89	0.98	1.61	0.84	0.98	1.09
TAC	13.2	14.6	16.9	18.1	18.4	17.2	16.1	16.3	16.0	15.3	14.3	13.4
	0.89	0.90	1.64	1.27	0.70	1.21	0.55	0.57	0.49	0.83	0.96	0.71
VER	21.3	21.5	23.5	25.9	27.3	27.7	27.6	27.9	27.6	26.6	24.4	22.3
	1.02	1.07	1.15	0.74	1.33	0.91	1.03	0.52	0.53	0.77	1.10	1.11
ACA	26.2	26.2	26.5	27.2	28.4	28.4	28.5	28.3	27.9	28.0	27.6	26.7
	0.76	0.83	0.69	0.52	1.04	0.68	0.58	0.76	0.72	0.57	0.67	0.74

ENSENADA	(ENS)	(31.51°N	116.37°W	13 m a.s.l.)
MERIDA	(MER)	(20.59°N	89.39°W	9 m a.s.l.)
TACUBAYA	(TAC)	(19.23°N	99.08°W	2,308 m a.s.l.)
VERACRUZ	(VER)	(19.12°N	96.08°W	16 m a.s.l.)
ACAPULCO	(ACA)	(16.50°N	99.55°W	~ 10 m a.s.l.)

We have also used solar radiation and atmospheric turbidity data, as determined by the Ångström turbidity coefficient β, recorded from 1975 to 1983 at the Solar Radiation Observatory of the Instituto de Geofísica (UNAM) located at the University campus in Mexico City.

The monthly normals of these two parameters over the period 1975-1981, and the corresponding standard deviations are given in Table 2. These values are based on measurements made between the 10:00 and 14:00 hrs. local time.

Table 2

Solar Radiation and Atmospheric Turbidity Data: Monthly Normals and Standard Deviations (Means: January 1975 - December 1981)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	775.1	800.9	788.3	725.5	629.3	716.5	656.5	655.8	696.9	690.0	713.7	707.4
(W/m^2)	144.4	138.8	120.7	135.3	129.1	152.8	137.4	129.1	126.3	141.6	134.6	136.0
β	0.132	0.140	0.157	0.222	0.303	0.221	0.261	0.269	0.225	0.227	0.178	0.169
	0.111	0.108	0.097	0.133	0.141	0.149	0.138	0.128	0.122	0.135	0.099	0.101

METHOD OF ANALYSIS

In order to study the impact on the troposphere of the March-April 1982 eruptions of El Chichón volcano, we have compared the 1982-1983 magnitudes of the departures of the monthly values of surface temperatures, solar radiation and atmospheric turbidity, from the smoothed monthly normals which represent the seasonal trends. This was done in order to carry out the analysis on data that are trend-free. As the data cover 12-month periods, the method used to determine the seasonal trends was the harmonic analysis of the monthly normals. For the temperature data, the seasonal trends were computed using the first two harmonics, while for the solar radiation and atmospheric turbidity data, which are influenced mainly by the prevalent air pollution, the first four harmonics were used. The magnitude of the departures are given in Tables 3 and 4. Since the distributions of the monthly departures, for each of the parameters studied, were proved to be essentially normal in character (the autocorrelation coefficients at lag one-month between points were not significant at the 95% confidence level), we have applied the usual procedure of standardization to our data. In this way, each data series of departures for each calendar month is expressed in the form of departure/standard deviation ratios. The standardization makes all departures statistically comparable in magnitude and permits a probability evaluation of their statistical significance.

Table 3

Monthly Temperature Departures (1982 - 1983) (in °C) from Smoothed Normals

OBS	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ENS	1982	−1.6	−0.1	−0.6	−0.4	−0.3	−1.6	−1.3	−1.3	−0.4	−0.6	−1.8	−2.2
	1983	−0.5	0.0	−0.2	−0.6	−0.2	−0.1	−0.5	1.2	1.8	1.0	−0.5	−0.4
MER	1982	1.9	1.5	0.4	1.2	0.3	0.4	−0.3	0.0	−0.2	−0.5	0.0	0.2
	1983	−0.9	−1.9	−2.4	−1.2	1.4	0.6	−0.8	0.0	0.5	0.4	0.1	0.8
TAC	1982	1.6	0.3	1.1	1.6	0.0	1.6	0.0	0.7	1.0	0.2	0.6	0.6
	1983	−0.7	−1.2	−0.2	1.5	3.2	2.6	0.3	0.8	0.3	0.2	1.2	1.1
VER	1982	1.5	0.5	0.6	0.8	0.3	1.3	0.2	0.2	0.0	−0.1	−0.3	−0.1
	1983	−0.6	−0.2	−0.4	−1.2	0.2	1.5	−0.1	0.6	0.0	−0.5	0.4	0.3
ACA	1982	−0.7	0.4	0.1	0.8	0.6	0.3	0.2	1.3	0.1	−0.2	−0.2	−0.7
	1983	0.2	−1.0	−1.3	−1.0	−0.2	1.2	0.4	1.0	−0.4	0.2	0.0	−0.2

Table 4

Monthly Departures (1982-1983) of direct solar radiation (W/m^2) and the Ångström β turbidity coefficient from Smoothed Normals

	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Δ	1982	191.2	190.5	175.8	88.6	152.1	−184.2	−163.2	−82.3	−124.9	−134.6	−152.8	−172.3
(W/m^2)	1983	131.2	67.7	74.6	91.4	219.8	− 39.1	−136.7	−66.3	− 6.3	− 23.7	− 34.9	− 38.4
$\Delta\beta$	1982	0.129	0.127	0.128	0.053	0.122	0.172	0.148	0.057	0.098	0.093	0.097	0.135
	1983	0.070	0.029	0.032	0.065	0.239	0.003	0.096	0.030	−0.049	0.023	0.012	0.002

Figures 1 show these standarized departures. The dashed lines in these figures represent departures equal to twice the standard deviation.

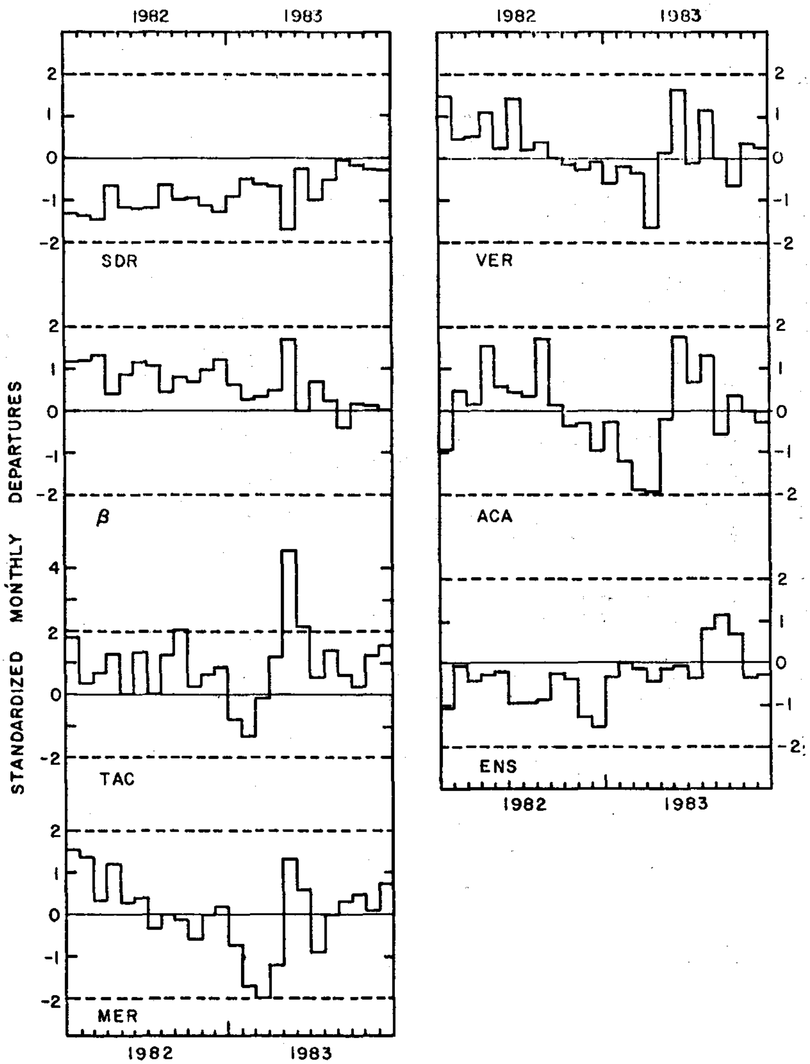

Fig. 1. Standardized monthly departures from normals during the years 1982 and 1983 for data given in Tables 1 and 2. The dashed lines represent the 95% confidence levels.

RESULTS AND DISCUSSION

Inspection of the monthly departures profiles in Figures 1 reveals a number of features that deserve comment, notably as follows:

1. During the summer of 1982, following the eruptions of El Chichón, the temperature departures, between 32° and 16°N on the Mexican territory, were in general positive, becoming larger (approximately +1.6°C in Tacubaya and +1.3°C in Veracruz) in June. Nevertheless, all the values are well within the range ($|x/\sigma| \leqslant 2.0$) of the data of the previous 20 years. The same is true for the solar radiation and atmospheric turbidity departures. These transient effects on surface temperature after an eruption were also observed during the Saint Helens eruptions by Robock and Mass (1982).

2. A general cooling trend started in May-June 1982 (one to two months after the eruptions) and ended in February-March 1983. This cooling trend, most clearly seen in Merida, Acapulco and Veracruz, and which lasted for nearly one year, was found to be statistically significant when the Spearman rank correlation (r_s) test was applied. In fact this test, which measures randomness against the alternative of trend, did not produce a single significant result such as those found in 1982-1983, during the previous 20 years of observations.

   This result can be explained in terms of theoretical results which have predicted important effects upon climate by volcanic eruptions (Pollack *et al.*, 1976; Harshvardhan and Cess, 1976; McCracken and Luther, 1984; Robock, 1984) if one takes into account the experimental findings by NASA aircraft missions (McCormick *et al.*, 1984) and the optical particle measurements made on balloon ascents (Hofmann and Rosen, 1984). These measurements confirmed the existence of two stratospheric layers, one below 20 km, moving slowly towards higher latitudes, and another above 20 km; constrained to a latitudinal belt between about 10°S and 30°N for approximately 6 months.

   Due to the size of the stratospheric aerosol at 25 km (main mode radius ~0.3 μm), we believe that this layer was the responsible of the observed cooling trend. The physical explanation is straightforward and has been given by Hansen *et al.* (1978) using a one-dimensional radiative-convective model. The sulfuric acid is highly reflective to solar radiation and thus tends to decrease the amount of solar radiation absorbed by the earth-atmosphere system. The aerosols, on the other hand, also interact with the thermal radiation as it was observed with the Solar Mesosphere Explorer Satellite (Barth *et al.*, 1983), causing a warming of the system via a greenhouse effect. However, the size of the aerosols imply a very small optical thickness in the infrared for the greenhouse effect to exceed the albedo effect. Hence, a decrease in the tropospheric temperature is expected.

During the whole period of the cooling trend, the solar radiation field showed a slow tendency to recover, while the turbidity coefficient showed a corresponding decreasing tendency.

3. The end of the cooling trend, in February-March 1983, was marked by a sudden increase of temperature, with the maximum being reached in May-June 1983. This temperature increase was coincident with a drastic diminution of the direct solar radiation (approximately 150 W/m^2) and a rapid increase of the Ångström turbidity coefficient. These departures were even greater than those observed the year before, after the eruptions of El Chichón.

   The above observational facts may be related to the removal processes of the volcanic stratospheric aerosol particles. Hofmann and Rosen (1983a) found that the two aerosol layers were decaying exponentially with time decay of the order of 8.5 and 7.6 months for the layers at 25 km and 15 km, respectively. These results imply that during May-June 1983, about 60% of the aerosol mass density was removed from the stratosphere and spreading latitudinally, partially descending into the troposphere. The results of the NASA aircraft mission of May 11-17, 1983 show the highest aerosol backscatter ratio, at $\lambda = 0.6943\ \mu m$ for an altitude between 18 - 21 km (Figs. 20 to 23, McCormick *et al.*, 1984). The latter fact may be associated with the increased solar radiation extinction at the ground. To complete a greenhouse effect that would explain all these observational results, one needs to have information on infrared radiation. Unfortunately, we do not have it.

CONCLUSIONS

The observational results here reported show the following facts:

1) A regional (16^o- 30^oN) cooling trend at the ground which started in May-June, 1982 and ended in March-April 1983. The highest negative anomaly was present during winter of 1982 - 1983. These results are in agreement with most of the results predicted with theoretical models of atmospheric impact of volcanic eruptions.

2) A regional (16^o- 30^oN) short-period warming at the ground after the cooling trend during May-June 1983. The warming is simultaneously present with extinction of solar radiation and increase of atmospheric turbidity. When one compares these results with those experimental ones, determined from balloon ascends and aircraft platforms, it is found that this tropospheric short period warming may be due to the descent into the troposphere of the volcanic (H_2SO_4) stratospheric aerosol during the removal processes. To consider a greenhouse effect it would be necessary to study infrared radiation which we do not have at present at our disposal.

3) While the observed low-level cooling over Mexico appears to be a plausible effect of the volcanic eruptions, it is difficult to disentangle this regional cooling from hemispheric warming and cooling patterns evidently associated with the 1982 - 83 El Niño (Quiroz 1983b, Rasmusson and Hall, 1983). These patterns were characterized by bands of warming in the tropics (the tropospheric warming being greatest in the east Pacific), cooling near 30^oN (see negative anomalies in Ensenada), and intense warming over middle to high latitudes of the North American and Eurasian continents (see Figs. 8, 15, 23 and 24 of Quiroz 1983b). Data available after winter 82 - 83 (Quiroz, private communication, 1984) indicate a dampening of these patterns by summer 1983, consistent with the change in sign of the surface temperature anomalies observed over Mexico.

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