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Extinction of short wave solar radiation due to El Chichon stratospheric aerosol

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RESUMEN

Utilizando insolación derivada de satélites meteorológicos (Tarpley, 1979) se desarrolla un método para estimar la reducción de la radiación solar de onda corta debida a la presencia de aerosoles estratosféricos producidos por las erupciones del volcán El Chichón (marzo 28-abril 4, 1982). Siete imágenes digitales diarias obtenidas bajo condiciones de cielo despejado durante mayo de 1982 a diciembre de 1983, se mapean en una malla de 1 × 1 longitud-latitud de México. Las condiciones de cielo despejado se determinan usando datos de duración de la insolación en algunos puntos de la malla. La resolución espacio-temporal de la radiación solar derivada del satélite permite estudiar, a través de la extinción de la radiación incidente, la evolución de la capa de aerosol estratosférico.

Los resultados se expresan como anomalías porcentuales de la extinción de la radiación solar con respecto a los valores medios de las imágenes digitales correspondientes a 1984: Durante mayo de 1982 valores altos de la extinción se observaron en casi todo México; de junio a agosto, la radiación solar incidente presentó valores casi normales, cuando los vientos estratosféricos del Este se encontraban bien organizados desplazando al aerosol hacia el Oeste. Después de septiembre de 1982, la extinción fue aumentando para alcanzar sus valores máximos en diciembre de 1982 (27.5%). De enero a mayo de 1983, la extinción permaneció con valores altos pero variables, entre 10 y 22%. De junio a agosto de 1983 nuevamente la radiación solar incidente mostró valores cercanos a los normales en casi todo el país, aunque algunas áreas permanecieron con anomalías significativas (13%). De septiembre a diciembre de 1983 la extinción de la radiación solar varió entre 16 y 14% mostrando que la estratosfera aún contenía una gran cantidad de aerosol residual. El decaimiento de la perturbación se comportó como un oscilador armónico amortiguado con variaciones estacionales cuyos máximos y mínimos ocurrieron en el invierno y verano locales, respectivamente.

ABSTRACT

Using satellite-derived insolation (Tarpley, 1979), a method is developed to assess total short-wave radiation depletion due to El Chichon stratospheric aerosols under cloudless conditions. Seven daily digital images are mapped on a 1x1 longitude-latitude grid of Mexico from May 1982 to December 1983. Cloudless conditions are determined using hourly sunshine data at several of the points of the array. The spatial and temporal resolution of satellite-derived irradiance permits the study of the evolution of the aerosol layers through the extinction of solar radiation.

The results are expressed as extinction anomalies with respect to the mean values of the corresponding digital images of 1984. During May 1982 high extinction values covered most of Mexico. From June to August 1982 solar irradiance returned almost to normal values as easterlies were well organized shifting the aerosol cloud westwards. After September 1982 solar radiation extinction increased reaching the highest values in December 1982 (27.5%). During January to May 1983 extinction remained high but variable, between 10 to 22%. From June to August 1983 solar radiation returned again to normal conditions in most of the country although some areas persisted with important extinction anomalies (13%). During September to December 1983 solar radiation extinction remained between 16 and 14% showing that the stratosphere still contained a large amount of residual aerosol. The decay of the perturbation behave as a dampened harmonic oscillator with seasonal oscillation, maximum and minimum occurring in local winter and local summer, respectively.

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Introduction

Volcanic activity is one of the forcing functions that has been recently identified as responsible for short–term climate changes (Hansen *et al.*, 1978). Volcanic eruptions occasionally inject gases and particles into the stratosphere. The radiative effects of stratospheric volcanic aerosols produce stratospheric warming (Newell, 1970; McInturff *et al.*, 1971; Labitzke and Naujokat, 1984) and tropospheric cooling which has been studied either using air temperature records and oxygen isotopes in deep–sea (Savin, 1977) or ice-core sediments (Legrand *et al.*, 1988; Sigurdsson, 1990. Volcanic sulfuric aerosols interact both with the short-wave incoming solar radiation through absorption (Neumann, 1973, Neumann and Graber, 1976) and scattering (Ramanathan *et al.*, 1987) and with the emitted long–wave terrestrial and atmospheric radiation through absorption (Harshvardhan and Cess, 1976; Pollack *et al.*, 1976; Ramanathan *et al.*, 1987; Kondratyev, 1988). The increased stratospheric long–wave radiation absorption would be responsible for the observed stratospheric warming meanwhile the enhancement of diffuse reflectivity of the atmosphere for the short-wave incoming solar radiation would be responsible for the tropospheric cooling determined through radiative transfer calculations (Hansen *et al*, 1978).

Ground–based measurements of solar radiation have documented the presence of volcanic clouds at different locations during the eruptions of Mount Agung in 1963 and El Chichon in 1982. The main results show increases up to 400% of the aerosol optical depth resulting in reductions between 21 to 33% in the direct and increases in the diffuse short–wave radiation between 80 to 200%. The total short-wave radiation decreases only between 5 and 10% (Dyer and Hicks, 1965; Viebrock and Flowers, 1968; DeLuisi and Herman, 1977; DeLuisi *et al.,* 1983; Nagaraja Rao and Bradley, 1983; Baker *et al.*, 1984; Wendler, 1984; Hay and Darby, 1984).

A simple method that uses satellite–derived insolation (Tarpley, 1979) to determine total short–wave radiation extinction (absorption and scattering) under cloudless conditions is presented below. It was applied to measurements made over Mexico during the two years following the El Chichon volcanic eruptions of March-April 1982.

Solar irradiances

Solar irradiances at the ground were determined for Mexico by Justus and Tarpley (1984) for the period May 1982–December 1984 using the digital visible data base obtained from the radiometers mounted on the geostationary meteorological satellites (SM-2 and GOES-2) applying the statistical model of Tarpley (1979). This data set was kindly provided to us by Dr. J. D. Tarpley from NOAA.

The archives consist of seven daily digital images which cover most of the Mexican territory (90-110°W, 16-30°N) accessed from GOES-East at different zenith angles, i.e., sampling times (1300, 1500, 1700, 1800, 1900, 2100 and 2300 GMT). The spatial resolution is 1 × 1 longitude-latitude degrees. Therefore the matrix D_k $(\mathbf{X}_{i,\ j})$ represents the kth-image, i.e., $1 \leq k \leq 7$ and $90 \leq i \leq 110$; $16 \leq j \leq 30$. A point (i, j) means a point of longitude–latitude (ϑ, φ) on the array. Further details of the data management are found in Galindo *et al.* (1991).

Error estimate for mean daily irradiances

The coefficients that enter into Tarpley's model (Tarpley, 1979) to determine solar irradiance at the ground from satellite data were obtained for the region of the Great Plains in the United States. Therefore, it is necessary to have an estimation of the errors generated when using the model in other latitudes with different surface properties (albedos) and climatological conditions.

A validation of monthly estimates of global solar radiation for Mexico and Uruguay (1982-1983) against ground–truth data obtained from calibrated pyranometers *showed standard errors less than 10%.* Furthermore, using the obtained regression equation for Mexico City, the monthly satellite estimates for 1984 when compared against pyranometric data *showed a standard error ranging between 3 and 5%* (Galindo, 1987).

The above quoted figures indicate that the estimation is quite reliable even though the model derived coefficients do not correspond to the actual physical conditions.

Sunshine data

Hourly sunshine data for the period 1982-1984 were provided from the Servicio Meteorológico Nacional for each of the 78 Meteorological Observatories disseminated all over the country.

An hourly data base was prepared in agreement with the satellite–sampling times. To assure cloudless conditions, only the data which read 10 decimals within an hour were used. The above data were matched with the satellite–derived maximum irradiance values for each point of the grid.

Determination of total short-wave irradiance anomalies

For each of the longitude–latitude points a daily mean percentage anomaly of total short-wave irradiance is defined as follows:

$$\mathbf{A} = [\mathbf{X}_{i,\ j} - \underline{X}_{(i,\ j)84}]/\underline{X}_{(i,\ j)84} \cdot \mathbf{100} \tag{1}$$

where $(i,\ j)$ denotes as above, a point of longitude–latitude on the array. $\mathbf{X}$ represents the daily mean solar irradiance for each of the months from May 1982 to December 1983. $\underline{X}$ is the mean monthly value for 1984. Therefore, equation 1 represents a comparison of measured irradiance values under cloudless conditions during the period of study *relative* to those obtained during 1984. Negative anomalies denoted *increased* solar radiation extinction and are attributed to the presence of the El Chichon stratospheric sulfuric aerosol layers.

Results

Evolution of the stratospheric volcanic aerosol cloud

The temporal and spatial evolution of the El Chichon stratospheric perturbation over Mexico is studied using the solar irradiance data. Only *increased* mean monthly anomalies are plotted at corresponding grid points, spaced one degree in longitude and latitude. The unmarked areas indicate that incoming solar radiation was apparently *unaffected* after the El Chichon eruptions. In Figure 1.1 it is shown that during May 1982 almost two thirds of Mexico was covered by increased radiation extinction which reached a maximum of 19.8%. Exceptions were the northwestern part and some patches between Yucatan and the State of Veracruz.

During June 1982, a return to normal conditions was observed. Only some increased radiance extinction is seen on the northeast at the border with the United States and at the Yucatan Peninsula. The maximum solar radiance extinction was 11.2% (Figure 1.2).

The trend of return to normal conditions prevailed over Mexico during the months of July and August (Figures 1.3 and 1.4).

1.1

1.2

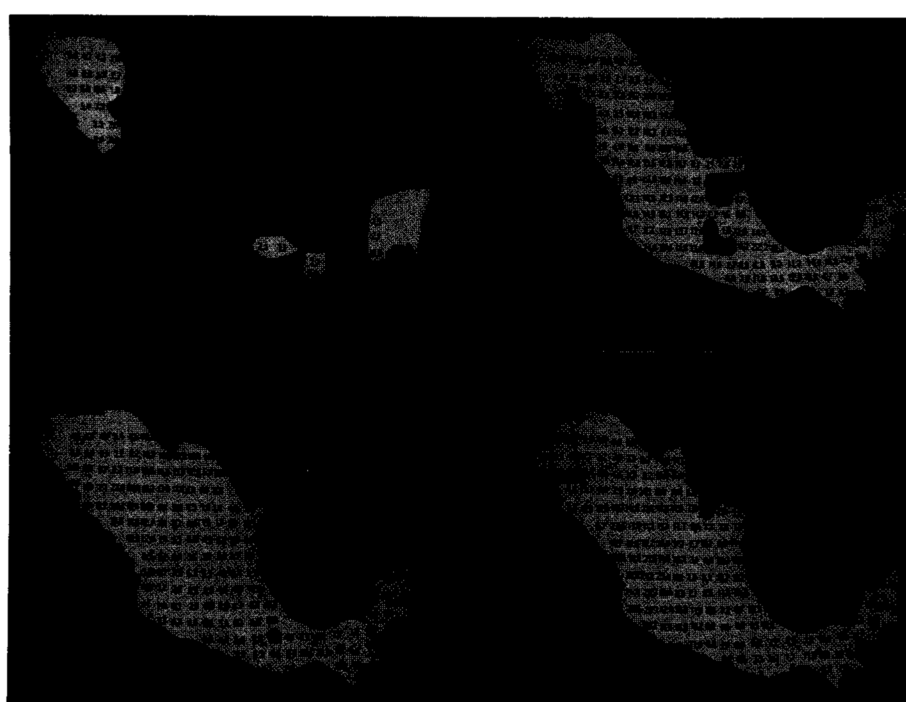
1.3

1.4

Fig. 1. Mean monthly solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. 1.1 May; 1.2 June, 1.3 July and, 1.4 August 1982, respectively.

2.1

2.2



2.3

2.4

Fig. 2. Mean monthly solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. 2.1 September; 2.2 October, 2.3 November and, 2.4 December 1982, respectively.

During September 1982 solar irradiance anomalies were manifested as several patches along the country, the largest of them was located in the northwestern part of Mexico. Maximum radiance extinction was 8.8% (Figure 2.1).

In October 1982 about 95% of the country was again affected by reduced solar radiation flux (increased extinction). Only a small part of the northeast at the border with Texas and Luisiana in the USA, was unaffected or showed positive irradiance anomalies. The maximum extinction was 22.2% (Figure 2.2).

The above situation remained during November 1982. Maximum solar radiance extinction was 23% (Figure 2.3).

December 1982 showed the largest depletion of solar radiation over most of the country. Maximum extinction was 27.5% (Figure 2.4).

In Figures 3.1 and 3.2 it is shown that the distribution of the increased radiance extinction for January and February 1983 is quite similar. Non-negative anomalies are growing from the East. The largest depletion of solar radiation was found over western Mexico. Maximum extinction were 16.8% and 22.3%, respectively.

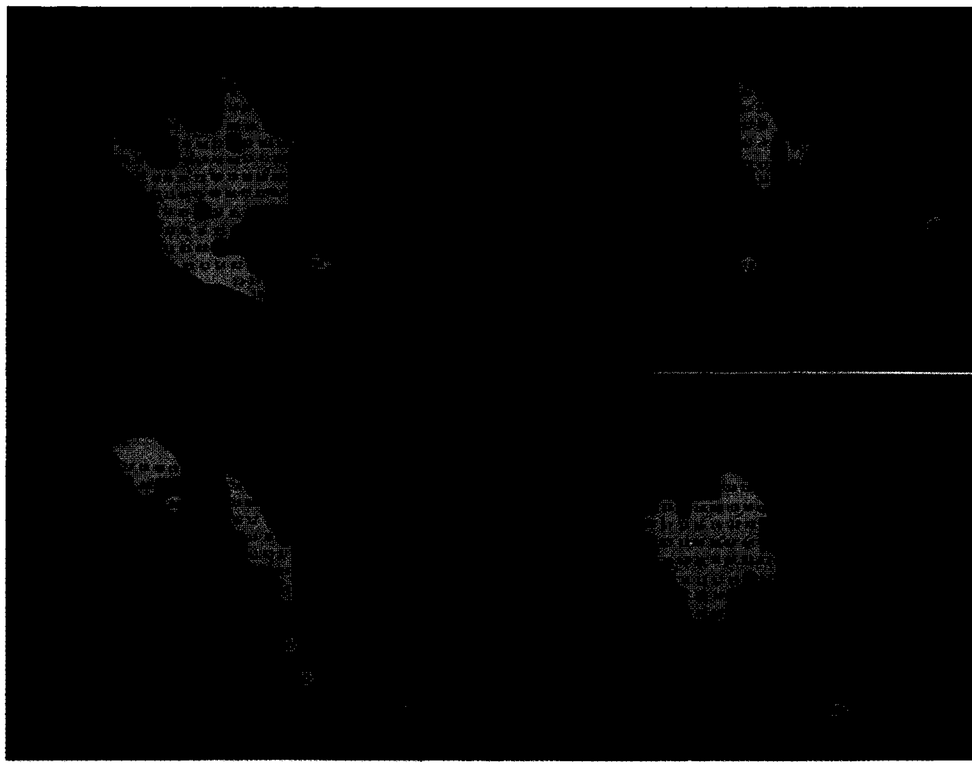
During March and April 1983 (Figures 3.3 and 3.4). It is seen that the increased extinction of solar radiation is broken into several patches, the largest of them concentrated over the northwestern part of Mexico. Although during April 1983 there is also a large area with increased solar radiation extinction extending northwards over the coastal plains of the Gulf of Mexico, from the Yucatan up to the border with Texas. Maximum extinction was 11.3% and 20.1%, respectively.

Fig. 3. Mean monthly solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. 3.1 January; 3.2. February, 3.3. March and, 3.4 April 1983, respectively.

The month of May 1983 shows that solar irradiance deficit covered most of the country. The maximum extinction is 21.4% (Figure 4.1).

The months of June, July, and August 1983 show, as for the same month of 1982, a return of solar irradiance to normal conditions in most of the country. However there are larger areas with increased extinction as in the summer of 1982. Maximum extinctions are 13.2%, 13.2 and, 13%, respectively (Figures 4.2 , 4.3 and 4.4).

4.1 4.2



4.3 4.4

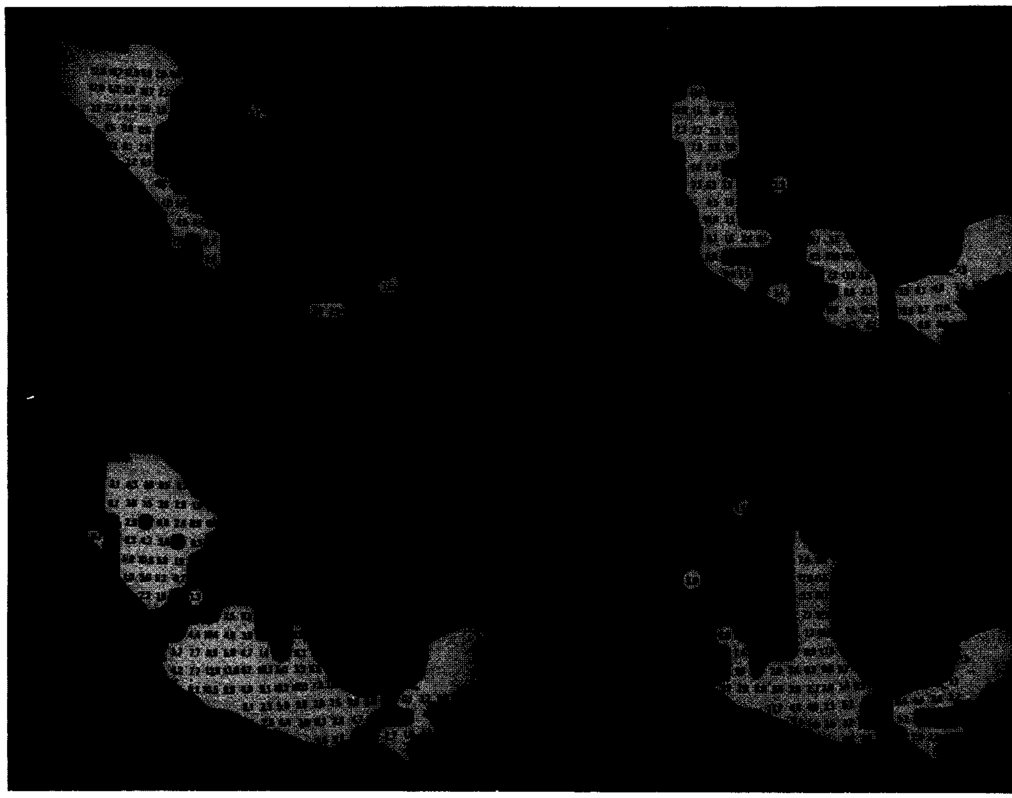
Fig. 4. Mean monthly solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. 4.1 May; 4.2 June, 4.3 July and, 4.4 August 1983, respectively.

In September and October 1983 the distribution of anomalous radiance extinction is shown as broken patches with a trend to increase. During September 1983 most of the northwestern part of Mexico is covered with increased radiance extinction (Figure 5.1), but in October, two large broken areas located at the East covering the southern part of Yucatan and part of Oaxaca, Puebla and Veracruz appeared (Figure 5.2). Maximum extinction was 12.6% and 16%, respectively.

The months of November and December show an important increase of anomalous radiance extinction and although they are considerable in size, they cover less territory as during the same months of 1982. The maximum extinction was 13.9 and 13.6%, respectively (Figures 5.3 and 5.4).

It is noticeable in all of the figures here presented that solar radiance extinction *under cloudless conditions*, attains quite different values on the grid from one point to other. This result shows that the distribution of solar radiance extinction turns out to be inhomogeneous, i.e., the volcanic stratospheric aerosol layer is indeed quite inhomogeneous in agreement with theoretical results (Harshvardhan, 1979).

5.1 5.2



5.3 5.4

Fig. 5. Mean monthly solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. 5.1 September; 5.2 October, 5.3 November and, 5.4 December 1982, respectively.

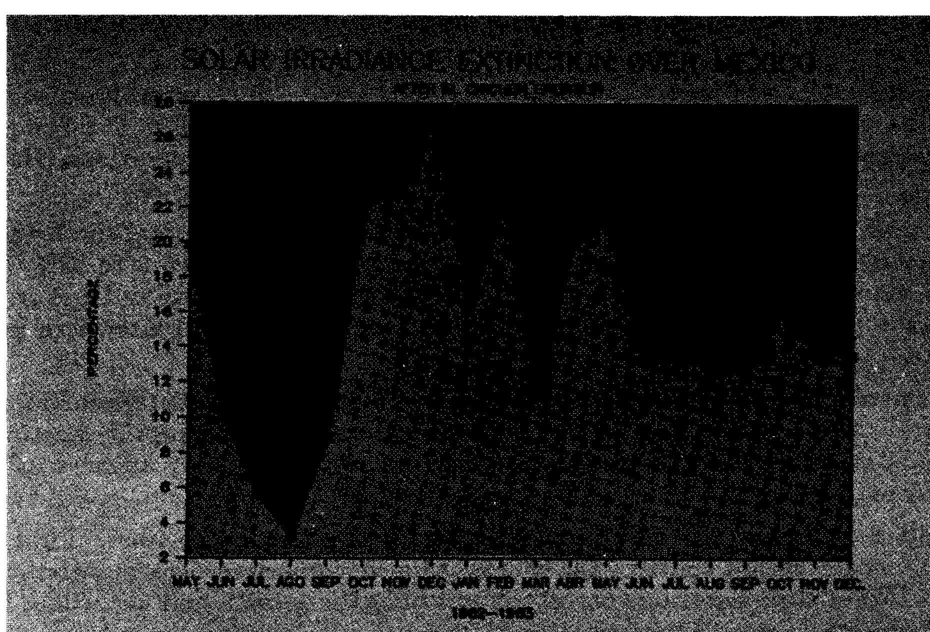


Fig. 6. Monthly maximum solar radiance extinction over Mexico under cloudless conditions due to El Chichon stratospheric aerosol layer. From May 1982 to December 1983.

In order to study the temporal evolution of the El Chichon stratospheric perturbation in Figure 6 are represented the observed maximum extinction monthly values irrespective of its position on the grid. It is seen that the minumum values were reached in summer 1982 and 1983 while maximum values are found in winter, particular that of 1982-1983. During the year of 1983, solar radiance extinction over Mexico remained elevated. From January to May there is a saw tooth behavior; then a platteau near 14% is seen from June to December. It seems that the incoming solar radiance flux remained below average during 1984. In fact satellite occultation measurements from May 1985 showed that the stratosphere contained a large amount of residual injected aerosol from El Chichon volcanic eruption (Kent *et al.*, 1991; Yue *et al.*, 1991). Since the anomalies reported here are *relative* to solar irradiances measured during 1984, they underestimate the real radiance depletion. Solar radiance extinction over Mexico between May 1982 to December 1983 behaves as a dampened harmonic oscillator with seasonal variations, a minimum in local summer and a maximum in local winter, respectively. This fact is also reported for stratospheric aerosol optical depth calculated from Stratospheric Aerosol and Gas Experiment II (SAGE II) data set (Yue *et al.*, 1991).

Discussion

The use of satellite–derived solar irradiance for monitoring the growth and evolution of stratospheric aerosol layers according to the method presented here opens new possibilities for understanding the behavior of the aerosol clouds and its temporal effects on the solar radiation field.

The month to month monitoring shows that the volcanic aerosol layer varied quite rapidly, particularly during summer 1982 when a return to normal conditions was observed and the stratospheric easterlies were well organized (Labitzke and Naujokat, 1984) and the quasi–biennial oscillation was at its maximum easterly phase with stratospheric winds from the east at about 25 m/sec for the region between 10 N and 10 S (Matson and Robock, 1984). In summer 1983 there is also a trend of return to normal conditions also associated with the stratospheric easterly winds.

Solar radiance extinction *under cloudless conditions* shows quite variable values from point to point on the grid. The randomness of this distribution is related to the *inhomogeneity* of the volcanic stratospheric aerosol in agreement with theoretical considerations (Harshvardhan, 1979).

The high values of solar radiance extinction reported here, show that total short-wave radiation is severely affected. Monthly maximum extinction values rank between 3 to 28%. This cloud–free result is more in agreement with radiative transfer computations and not a relative *low sensitivity* of the global short–wave radiation as it has been reported elsewhere using ground measurements.

A comparison of the results reported here with aerosol optical depth determined for Vancouver (Hay and Darby, 1984) shows that the volcanic aerosol layers spread rapidly northward during November and December 1982 in agreement with the results of other authors using different techniques (Strong, 1984).

The method shown here can be improved in two different ways at least. First, using high resolution data would permit splitting the effects of the volcanic aerosols and water vapor clouds. Second, using longer time series one can study not only the growth and evolution, but also the time decay of the stratospheric perturbation.

Finally, since polar orbiting operational satellites monitor globally, the observation area can be expanded to trace the time and space evolution of the stratospheric aerosol cloud, relating these results to its climate impact.

Conclusions

The method presented here permits the study of the impact of the stratospheric volcanic aerosol on the incoming solar radiation. The spatial and temporal resolution of satellite–derived irradiance allows the analisis with great detail of the location and movements of the aerosol layers through the extinction of solar radiance. Sunshine data are used for identification of extinction values under cloudless conditions.

The results show that the depletion of solar radiation over Mexico after the El Chichon eruptions ranged between 3 and 28%. A return to normal conditions of the solar iradiance is observed during summer particularly in 1982 when the stratospheric easterlies were well organized. Maximum extinction values occurred during winter 1982-1983 and 1983-1984. The highest values are in December 1982 (27.5%). Minimum extinction values are found during summer, particularly in 1982.

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