

**THE POSSIBLE EFFECTS OF EL CHICHON ERUPTION ON
ATMOSPHERIC THERMAL AND CHEMICAL STRUCTURE
AND SURFACE CLIMATE**

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RESUMEN

Se sugiere que la inyección de óxidos de azufre y ceniza en la estratosfera desde la erupción de 1982 de El Chichón, alteraría el equilibrio radiativo-fotoquímico de la atmósfera de la Tierra, lo cual a su vez conduciría a los cambios en la temperatura vertical y la estructura química de la atmósfera y en el clima de la superficie. En este estudio se utiliza un modelo radiativo-convectivo-fotoquímico para computar la respuesta térmica y química de la atmósfera y el clima de la superficie a las concentraciones aumentadas de aerosol atmosférico resultantes de la erupción de El Chichón. Los recientes datos sobre el espesor óptico y las propiedades ópticas del aerosol obtenidos de las observaciones globales de la nube de El Chichón, se han utilizado como ingreso para la integración del modelo. El modelo permite concentraciones de aerosol y propiedades ópticas variables en el tiempo durante el ciclo de vida de la nube volcánica.

Los resultados preliminares muestran que durante el primer año después de la erupción, el promedio global de la temperatura superficial decrece aproximadamente 0.9°C mientras causa calentamiento significativo en la estratosfera inferior (hasta de 5°C). La atmósfera y la superficie alcanzarán sus valores de fondo de temperatura *grosso modo* de 3 a 4 años después de la erupción. También se discuten las implicaciones de la erupción de El Chichón para el ciclo fotoquímico del ozono estratosférico.

ABSTRACT

It is suggested that the injection of sulfur oxides and ash into the stratosphere from 1982 El Chichón eruption, would alter the radiative-photochemical balance of the earth's atmosphere which in turn leads to the changes in the vertical temperature and chemical structure of the atmosphere and surface climate. In this study one dimensional radiative-convective-photochemical model is used to compute the thermal and chemical response of the atmosphere and the surface climate to enhanced stratospheric aerosol concentrations resulting from the El Chichón eruption. The recent observational data on aerosol optical thickness and optical properties obtained from the global monitoring of the El Chichón cloud has been used as input to model integration. The model allows variable aerosol concentrations and optical properties in time during the life cycle of the volcanic cloud.

The preliminary results show that during the first year after the eruption, the global average surface temperature decreases by about 0.9°C while causing significant warming in the lower stratosphere (up to 5°C). The atmosphere and the surface will reach their background temperature values within roughly 3 to 4 years after the eruption. Also discussed are the implications of El Chichón eruption to stratospheric ozone photochemical cycle.

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1. INTRODUCTION

The effect of volcanic aerosols on the large scale climate of the earth has received a great deal of attention, particularly since the eruption of El Chichón in Mexico in April 1982. Since the aerosols in the atmosphere absorb and scatter both solar and terrestrial radiation, it is suggested that the injection of ash and sulfur oxides into the stratosphere by a large volcanic eruption such as El Chichón would alter the existing radiative energy balance of the earth's atmosphere which in turn leads to the changes in the vertical temperature and chemical structure and surface climate. The objective of this study is to investigate the thermal and chemical response of the atmosphere and the surface climate to the radiative perturbation caused by the enhanced stratospheric aerosol concentrations from the El Chichón volcanic eruption of April 1982.

2. THE CLIMATE MODEL

The model used for this study is a coupled one dimensional radiative-convective and photochemical diffusion model which takes into account the interaction of atmospheric chemistry on vertical temperature structure and surface climate (Wang *et al.*, 1976). Starting from the assumed chemical composition and vertical temperature distribution the basic procedure is to compute the local radiative heating and cooling and photochemical sources and sinks at each altitude to determine the new vertical temperature and chemical trace constituent structure with time marching method. The upward heat transfer by atmospheric motions is taken into account implicitly by simple numerical procedure called convective adjustment which was first introduced by Manabe and Strickler (1964). Using this procedure the model lapse rate is adjusted to the critical lapse rate (-6.5°K per km) whenever the critical lapse rate is exceeded in the numerical iterative calculations. In the model the relative humidity is kept fixed instead of absolute humidity and this allows the feedback effect between temperature and water vapour mixing ratio. The solar constant is assumed to be 1365 W/m^2 and the effective cosine of the mean zenith angle and the fractional daylight hour for day are set at 0.5. A single cloud type is assumed with fixed cloud top altitude at 6.5 km. The clouds are considered to be black in the infrared and the fractional cloud cover is fixed at 0.446 (Ramanathan *et al.*, 1976). Averaging of solar radiative heating calculations over clear and cloudy sky is performed at each time step using the fractional cloud cover as weighting factor. After initial experimentation with different values, 0.2 is adopted for the surface albedo. For the time marching the model uses Adams-Bashford scheme with 6 hour time step.

3. THE RADIATIVE TRANSFER MODEL

The solar radiation model used to compute the short wave solar heating within the atmosphere is based on the delta-Eddington method which is computationally ef-

ficient and fairly accurate (Joseph *et al.*, 1976). The model takes into account absorption and scattering by atmospheric gases (H_2O , O_3 , NO_2 and CO_2), aerosols and cloud droplets. To compute the infrared cooling or heating due to H_2O , O_3 , CO_2 and aerosols the analytical formulae for the mean transmissivities of finite frequency intervals derived by Kuo (1979) have been adopted. The mean transmission functions take into account the overlapping absorption between gases and the computed transmissivities agree well with detailed calculations.

4. THE PHOTOCHEMICAL MODEL

The photochemical model includes the important reactions affecting the concentration of ozone and other minor constituents in the stratosphere and the system consists of odd oxygen (O , $\text{O}(^1\text{D})$, O_3), the odd hydrogen (H , HO , HO_2), N_2O and the odd nitrogen (N , NO , NO_2 , HNO_3) chemical trace gases (Vupputuri, 1978/79). The concentrations of H_2O , H_2 and CH_4 which are required for photochemical calculations are specified based on observations. The interaction between volcanic aerosols and chemistry is allowed through the alteration of photodissociation rates of O_3 and NO_2 trace gases.

5. THE PERTURBED EL CHICHON AEROSOL MODEL

To determine the possible effect of increased stratospheric aerosol concentrations from El Chichón eruption on atmospheric thermal and chemical structure and surface climate two different model calculations have been made. In the first calculation we assume that the added stratospheric aerosols have a peak optical thickness of about 0.1 on a globally averaged basis and the aerosols also possess optical properties which do not vary in time. In the second calculation we allow both the perturbation optical thickness and the aerosol optical properties vary in time beginning from the date of El Chichón eruption as illustrated in Fig. 1.* The El Chichón aerosol optical properties chosen for this study are those reported in NASA Technical Memorandum 84959 (Bandeem and Fraser, 1982). The optical parameters (extinction coefficients, single scattering albedo, asymmetry factors) are derived as a function of wavelength assuming the aerosol particles are composed of 75% H_2SO_4 and 25% H_2O . During the first three months after the eruption we assume the optical properties of the ash for the El Chichón with imaginary refractive index of 0.002 (Patterson and Pollard, 1983) and later we switch the properties from El Chichón ash to El Chichón sulfuric acid and finally to background stratospheric aerosol properties. Since the added aerosol concentrations and the radiative characteristics vary in time and space in the real atmosphere we believe the results in the second calculation are considered to be more realistic than the first.

* In both calculations the altitude of peak aerosol concentration is assumed to be at 25 km (Labitzke *et al.*, 1983).

GLOBAL AVERAGE AEROSOL PERTURBATION MODEL FOR EL CHICHON.

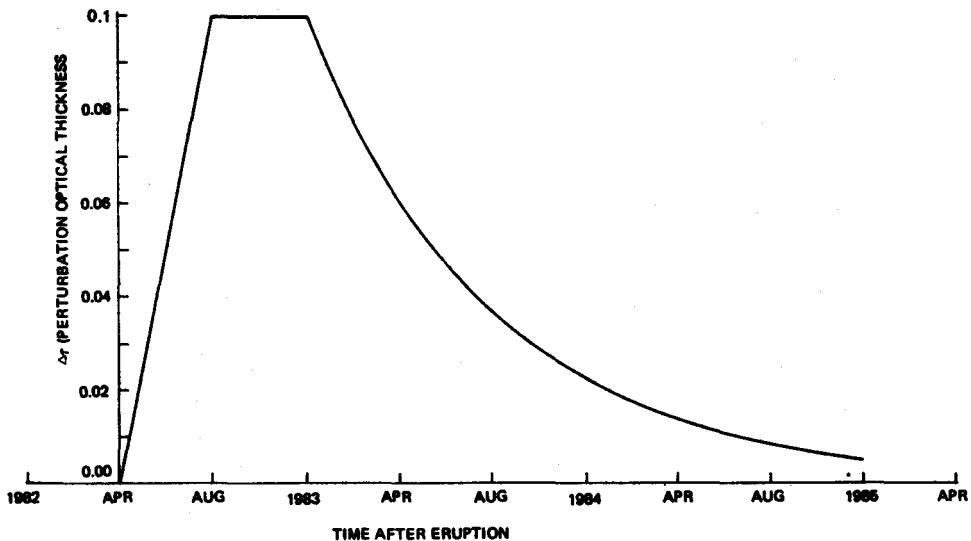


Fig. 1. The assumed variation of perturbed stratospheric aerosol optical thickness with time for the El Chichón volcanic cloud.

6. DISCUSSION OF MODEL RESULTS

Fig. 2 shows the computed vertical temperature structure with and without ozone interaction for the unperturbed atmosphere with background stratospheric aerosols. Also shown in Fig. 2 for comparison is the thermal structure for the 1962 US standard atmosphere. It is seen that the agreement between the model calculation with ozone interaction and the US standard atmosphere is generally very good except near the tropopause region. The discrepancy near the tropopause region may be attributed to the lack of horizontal and vertical transports of heat in the 1-D model. Note that the computed temperature values above 45 km in the fixed ozone case are overestimated compared to the US standard atmosphere suggesting that the observed US standard atmosphere ozone mixing ratio values may have been overestimated in that region. In Fig. 3 the computed vertical ozone distribution with interactive chemistry is compared with the ozone distribution in the US standard atmosphere. It can be seen that the two vertical distributions are very similar in shape although the computed ozone mixing ratio values are underestimated both below and above the level of maximum ozone mixing ratio. In the lower stratosphere the discrepancy can be attributed to the lack of horizontal transports in the model and above the level of ozone maximum horizontal transports do not play a significant role and it is possible that the US standard atmosphere ozone mixing ratio values may have been overestimated.

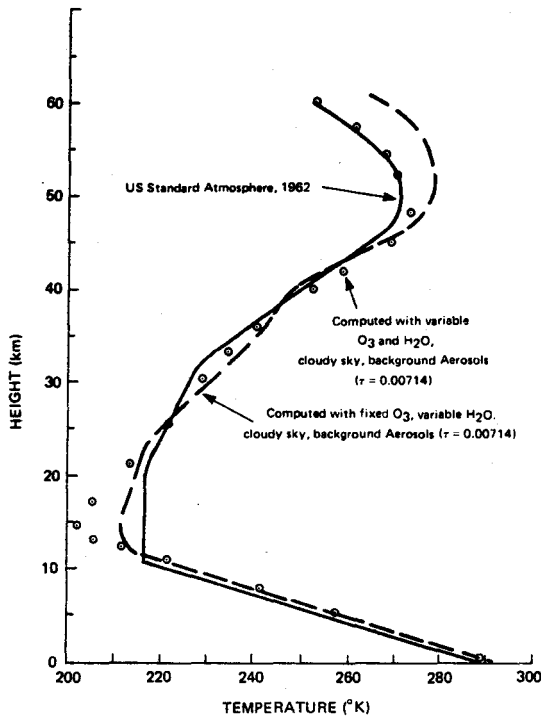


Fig. 2. The comparison of computed vertical temperature structure with that of 1962 U.S. standard atmosphere.

Before we discuss the second model calculations for the variable aerosol model as described in Fig. 1, it is important to see how various feedback mechanisms affect the vertical temperature distribution and surface climate in the first model calculations with fixed aerosol perturbation. Fig. 4 shows the effect of fixed El Chichón aerosol perturbation on vertical temperature structure and surface climate for two different chosen optical properties. As shown in Fig. 4 the increased stratospheric aerosol concentration with peak optical thickness of 0.1 and aerosol composition consisting of 75% H_2SO_4 and 25% H_2O lead to about 0.9°C cooling near the surface while causing roughly 1.3°C heating at the altitude of peak aerosol concentration in the stratosphere (25 km). If the aerosol cloud on the other hand is composed of silicate ash which may be the case during the first month or so after the eruption, then it would lead to much enhanced heating in the stratosphere (4.5°C) and reduced cooling in the troposphere and at the surface (0.75°C). Fig. 4 also shows that the interaction of thermal radiation with aerosol cloud has the effect of enhancing the stratospheric heating (absorption of upwelling thermal radiation through the atmospheric window) and reducing the tropospheric cooling (counter radiation from the aerosol cloud). It is of particular interest to note that the strato-

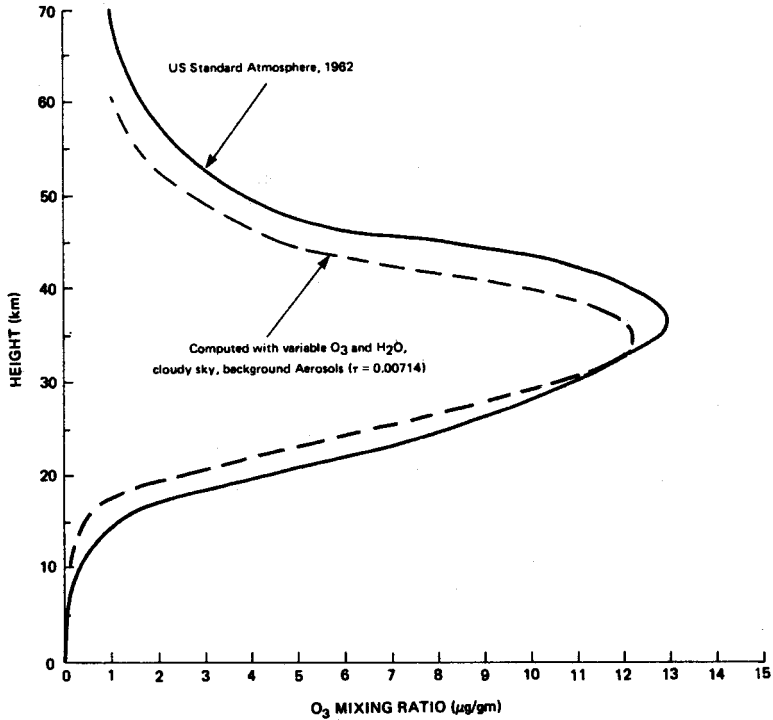


Fig. 3. The comparison of computed vertical distribution of ozone with 1962 U.S. standard atmospheric ozone profile.

spheric heating is completely dominated by the absorption of upwelling thermal radiation if the cloud consists of sulfuric acid droplets. On the other hand if the cloud consists of silicate dust, the absorption of solar radiation by the cloud still dominates the stratospheric heating.

The feedback effect between water vapour mixing ratio and temperature on the expected changes in the thermal structure from the El Chichón cloud is shown in Fig. 5. Note that the water vapour feedback effect leads decreased heating in the stratosphere (IR cooling due to increased water vapour) while causing increased cooling in the troposphere and at the surface (reduced greenhouse effect due to decreased tropospheric water vapour). The additional cooling due to water vapour feedback effect is nearly 30% of the total cooling at the surface for the sulfuric acid cloud while in the case of ash cloud the additional contribution is only 15%. Fig. 6 shows the effect of El Chichón cloud on vertical ozone distribution while the feedback effect of ozone changes on the thermal structure is illustrated in Fig.

THE EFFECT OF EL CHICHON ERUPTION ON VERTICAL TEMPERATURE STRUCTURE

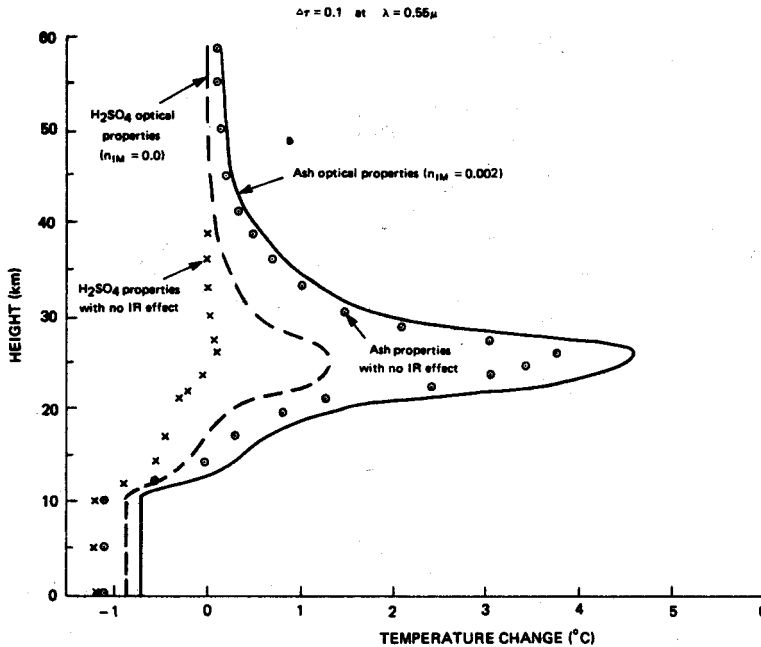


Fig. 4. Computed changes in the atmospheric and surface temperature due to El Chichón eruption assuming that the added aerosols in the stratosphere have a peak optical thickness of 0.1 (at $\lambda = 0.55\mu$). Calculations are shown for two different optical properties for the El Chichón cloud with and without the aerosol interaction in the thermal infrared radiation in the atmospheric window region.

7. It can be seen from Fig. 5, that the aerosol cloud from the El Chichón eruption has the effect of decreasing the ozone in the stratosphere. The ozone depletion may be attributed to the enhanced ozone photodissociation rates caused by the multiple scattering effects from the aerosol cloud and to the feedback effect of stratospheric heating on ozone mixing ratio. As illustrated in Fig. 7 the feedback effect of ozone changes on the vertical temperature structure is not very significant. However, it has the effect of cooling the upper stratosphere (reduced solar heating due to ozone depletion) slight warming in the lower stratosphere (self healing effect of ozone) and increased cooling at the surface (reduced greenhouse effect through 9.6μ ozone band).

THE EFFECT OF EL CHICHON ERUPTION ON VERTICAL TEMPERATURE STRUCTURE

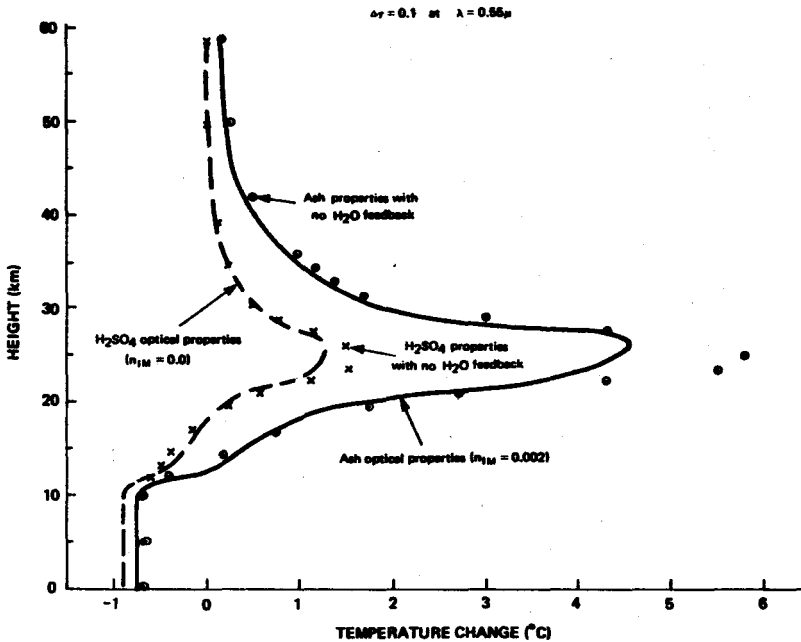


Fig. 5. Same as in Fig. 4 except the calculations are shown with and without the feedback effect between the water vapour mixing ratio and temperature.

THE EFFECT OF EL CHICHON ERUPTION ON VERTICAL OZONE DISTRIBUTION

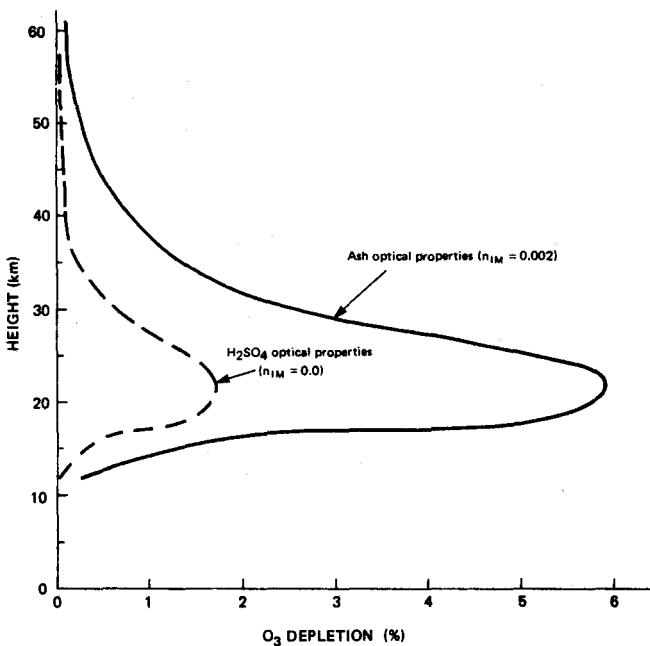


Fig. 6. Computed changes in the vertical ozone distribution (in %) due to El Chichón eruption. The assumed optical thickness for the added stratospheric aerosols is again 0.1 and the calculations are shown for two different assumed optical properties of the El Chichón cloud.

THE EFFECT OF EL CHICHON ERUPTION ON VERTICAL TEMPERATURE STRUCTURE

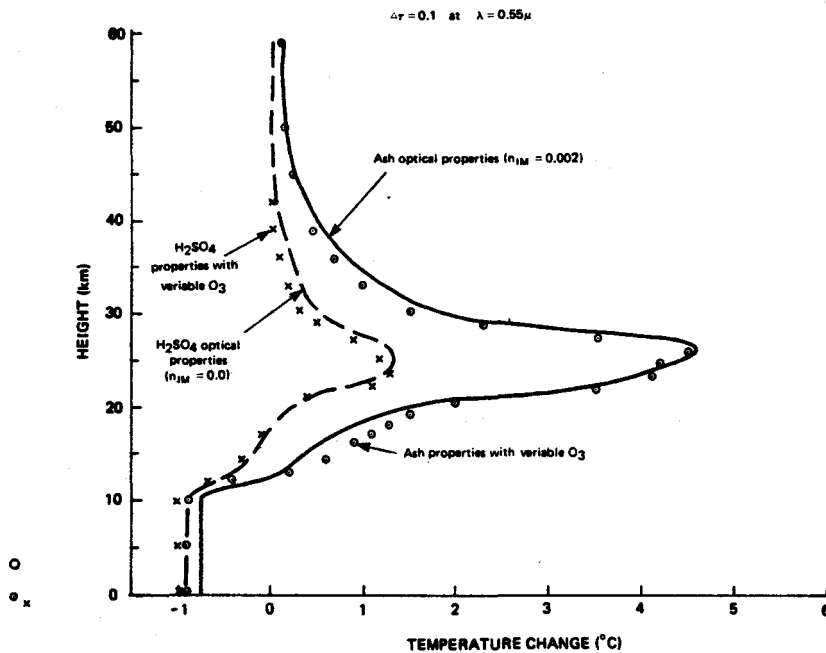


Fig. 7. Same as in Fig. 4 except calculations are shown with and without the feedback effect of ozone changes. Note the solid and dashed curves represent changes in temperature with fixed ozone while the changes for the variable ozone are marked by the circles and crosses.

In order to test the sensitivity of the altitude of peak aerosol concentration, additional calculations have been made by reducing the peak aerosol concentration altitude from 25 km to 17 km while keeping the optical depth of the cloud same as before for the ash cloud and its effect is shown in Fig. 8. It is clear from the Fig. 8 that by reducing the peak altitude of aerosol concentration one can expect reduced heating in the stratosphere and also reduced cooling in the troposphere and at the surface. Fig. 8 also shows that in the case of the sulfuric acid cloud with peak concentration altitude at 17 km one can also expect slight cooling above the peak altitude as opposed to slight warming when the peak concentration altitude is located at 25 km.

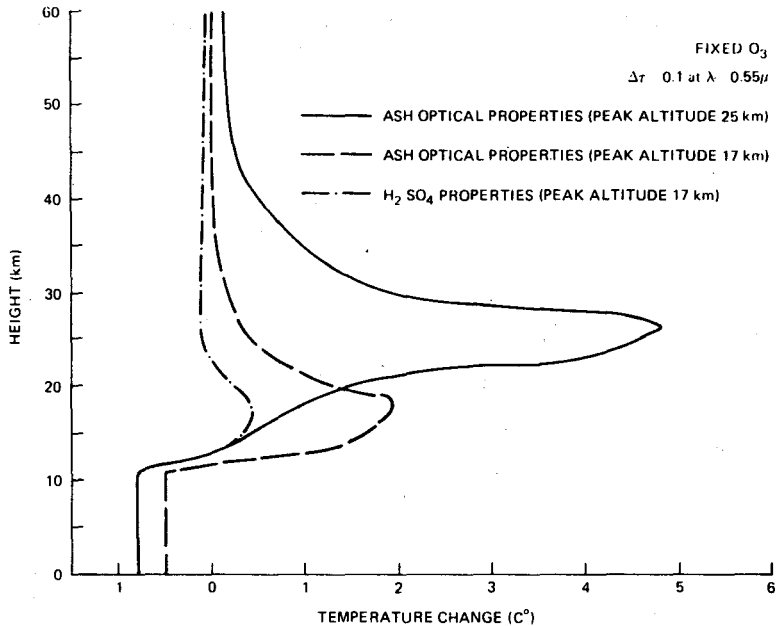


Fig. 8. Atmospheric and surface temperature changes representing the effects of lowering the altitude of peak aerosol concentration of the El Chichón cloud from 25 km to 17 km. Note the El Chichón sulfuric acid cloud with peak aerosol concentration height at 17 km leads slight cooling above the center of the cloud.

Fig. 9 shows effects of El Chichón volcanic stratospheric aerosol cloud on stratospheric temperature and surface climate in the second calculation in which the model allows the variation of both aerosol optical thickness and optical properties in time as described in Fig. 1. The variations of IR (reaching the surface) and net solar flux changes at the ground and the changes in the planetary albedo which would help to explain surface temperature changes are given in Fig. 10. It is worth noting from Fig. 9 that the stratosphere responds more quickly to the radiative effects of the El Chichón cloud compared to the troposphere. As indicated in Fig. 9 one might expect a maximum heating of about $4^{\circ}C$ at the peak altitude of aerosol concentration (25 km) in the stratosphere within 5 months after eruption date while it takes twice as long to reach the maximum cooling in the troposphere and at the surface. The maximum cooling of about $0.9^{\circ}C$ at the surface should be considered as the upper limit since the peak altitude of aerosol concentration for the cloud may shift to a lower altitude than 25 km specified in this study, in time due to settling effect. These computed variations of stratospheric heating and surface cooling are similar to those reported by Hansen *et al.* (1978) for the Agung erup-

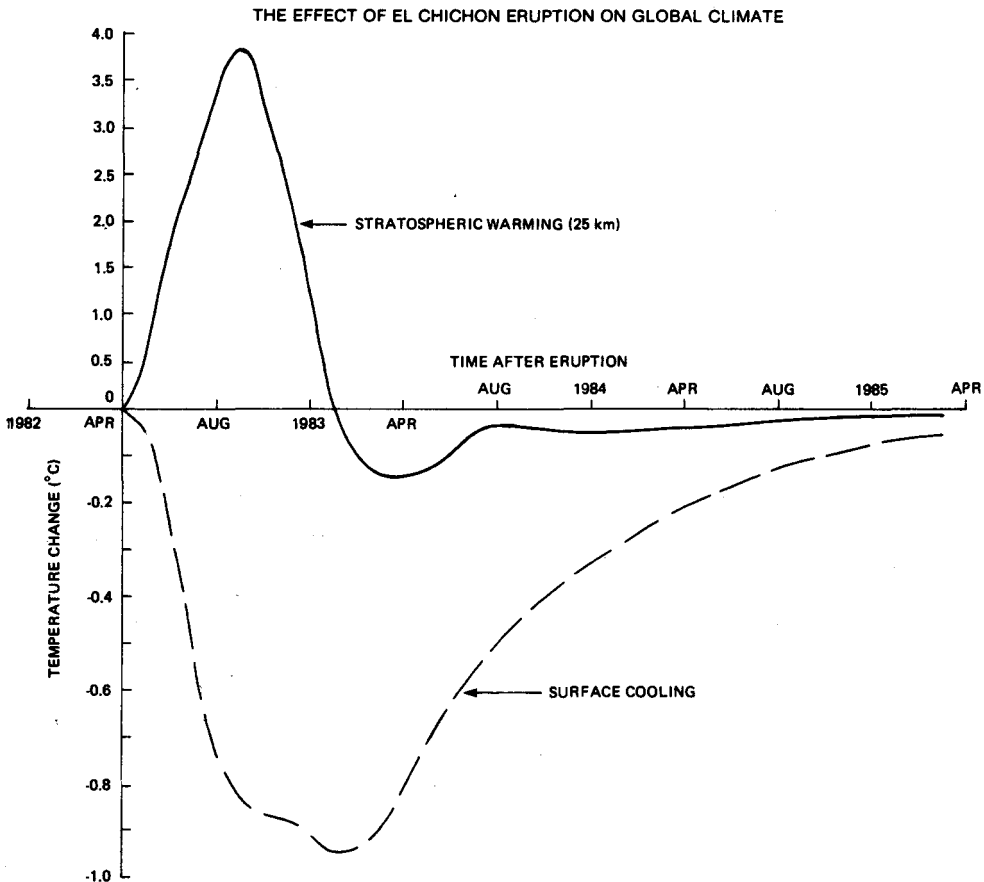


Fig. 9. Variation of stratospheric and surface temperature changes as a function of time for the El Chichón stratospheric aerosol cloud model shown in Fig. 1.

tion, although the present study does not consider the mixed layer ocean. Consideration of ocean mixed layer is not expected to alter the amplitude of temperature changes, but it could prolong the date of maximum surface cooling.

It is difficult to verify the computed cooling at the surface due to uncertainties in the observed temperature variations and climate noise. However, there is some empirical evidence to show that there is a sharp drop in temperature on a hemispheric basis following the major volcanic eruptions (Soufrière, Mont Pelée and Santa María in 1902 and Mt. Agung in 1963) although one is not certain of the mechanisms. The stratospheric heating however appears to be well documented following the El Chichón eruption (Labitzke *et al.*, 1983; Quiroz, 1983). For ex-

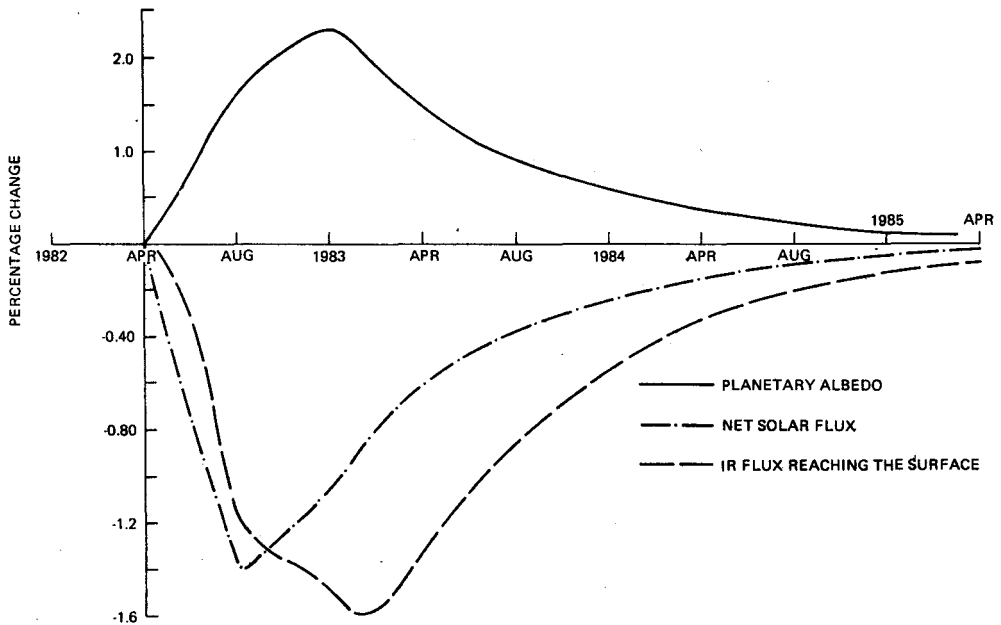


Fig. 10. Variation of thermal IR and net solar flux changes at the surface and changes in the planetary albedo (in %) as a function of time for the assumed El Chichón stratospheric aerosol cloud model.

THE EFFECT OF EL CHICHON ERUPTION ON GLOBAL WATER VAPOUR MIXING RATIO

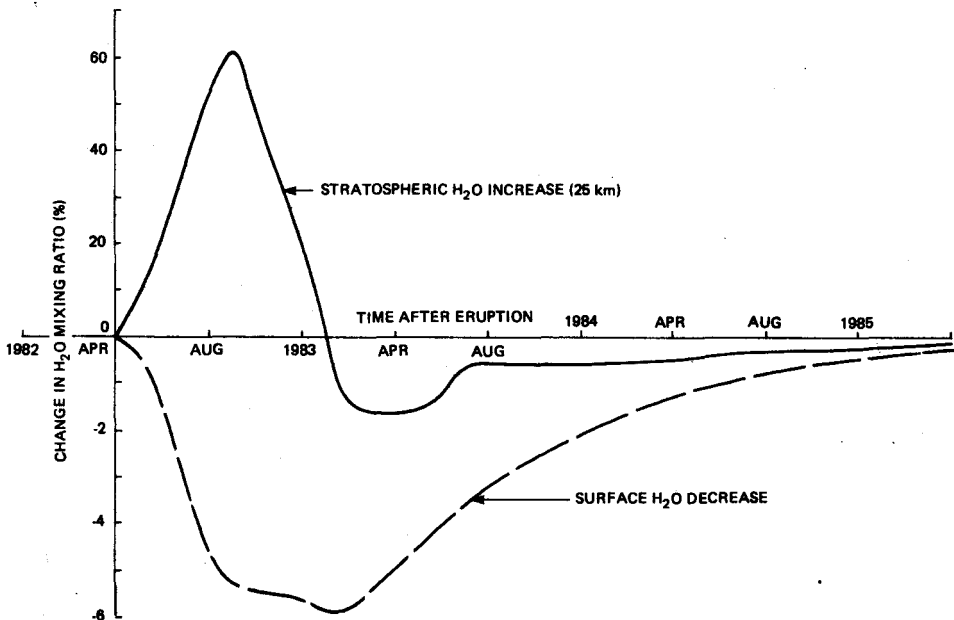


Fig. 11. Variation of water vapour mixing ratio changes (in %) in the stratosphere and at the surface as a function of time for the assumed El Chichón stratospheric aerosol cloud model.

ample Quiroz after careful analysis of stratospheric temperature observations by taking into consideration the temperature changes due to dynamic origin, El Niño event and QBO, reported an average temperature increase of about 2.5°C in tropics, at 3 mb level (24 km) during the mid summer following the El Chichón eruption. This value agrees well with the computed temperature increase of about 3°C during the midsummer at 25 km in the stratosphere. (See top curve in Fig. 9).

Figs. 11 and 12 show the computed variations of water vapour mixing ratio changes and changes in the total ozone column following the El Chichón eruption. As one would expect the water vapour mixing ratio changes simply follow the temperature changes since the saturation vapour pressure and hence the water vapour mixing ratio is a function of temperature (compare Figs. 9 and 11). The total ozone depletion curve (Fig. 12) also follows to some extent the temperature changes in the stratosphere (see the top curve in Fig. 9) although the multiple scattering effects from the aerosol cloud also contribute to the ozone depletion. It is interesting to note that the maximum depletion in the total ozone column occurs about a month later than the maximum heating in the stratosphere and this might help to explain the overshooting effect from heating to slight cooling in the stratosphere during the spring season in 1983 (see the top curve in Fig. 9). Based on the analysis of SBUV ozone observations Heath (1983) finds about 5% reduction in the total

THE EFFECT OF EL CHICHON ERUPTION ON TOTAL OZONE COLUMN

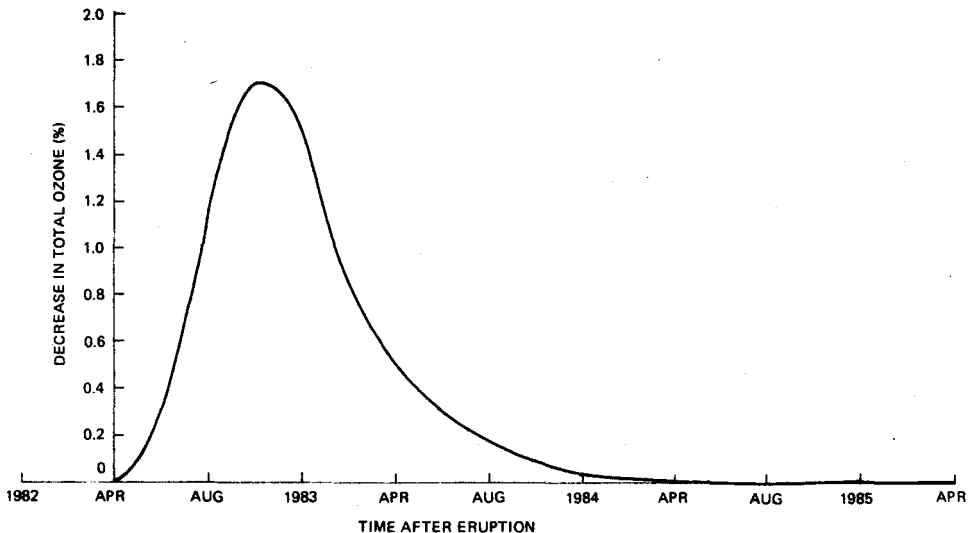


Fig. 12. Variation of total ozone depletion (in %) as a function of time for the assumed El Chichón stratospheric aerosol cloud model.

ozone column following the El Chichón eruption (private communication). This can be compared with roughly 1.8% maximum total ozone depletion computed in this study (see Fig. 12). Among the other uncertainties the discrepancy between the computed and observed ozone depletion may be attributed to the lack of consideration given to the HCl injections into the stratosphere that were known to have occurred following the El Chichón eruption.

7. CONCLUSIONS

Based on simple one-dimensional radiative - convective - photochemical model calculations the following tentative conclusions can be arrived.

- 1) The increased stratospheric aerosols from the El Chichón eruption leads to the maximum cooling of the troposphere and the surface by about 0.9°C during the first year while causing significant warming in the stratosphere (up to 4°C) within six months after the eruption date.
- 2) The interaction of the stratospheric El Chichón aerosol cloud with ozone photochemistry leads up to 1.8% depletion in the total ozone column which in turn has the effect of increasing the cooling at the surface and above the cloud center while causing slight warming below in the lower stratosphere.
- 3) Both the atmospheric and surface temperature and total ozone column are expected to reach their background values within 3 to 4 years after the eruption.
- 4) The upwelling of thermal radiation in the window region dominates the stratospheric heating only when the aerosol cloud consists of sulfuric acid droplets. Otherwise solar absorption dominates the heating even with small amount of ash present in the cloud.
- 5) The atmospheric water vapour feedback effect enhances the cooling at the surface between 15 and 30% depending upon the assumed optical properties for the volcanic aerosols.
- 6) Lowering the altitude of peak aerosol concentration within the cloud has the effect of decreasing both the stratospheric heating and surface cooling.

Despite the simplicity of the model and some uncertainties in the input parameters such as the optical properties of aerosols and photochemical data we believe the temperature and ozone changes computed in this study have the right sign and right order of magnitude. It is hoped that with additional data on physical and chemical properties of the aerosol cloud and its spatial distribution and further detailed analysis of temperature and ozone observations following the eruption will help to resolve some of the differences outstanding.

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