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GLOBAL TRANSPORT OF VOLCANIC AEROSOL FROM EL CHICHON ERUPTION STUDIED WITH A THREE–DIMENSIONAL CIRCULATION MODEL

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RESUMEN

Para estudiar la dispersión global de la nube volcánica de la erupción de El Chichón utilizamos el modelo tridimensional de circulación de la estratosfera desarrollado en el MIT-GIT. El modelo dependiente del tiempo se corrió para cuatro meses hasta fines de octubre de 1982. El inicio se proporcionó mediante las mediciones de la distribución del aerosol en latitud y altitud. La comparación de los resultados con los datos experimentales hecha los días 105 y 120 a partir del comienzo de la simulación muestra una concordancia razonable, si bien la concentración resultante del modelo está recorrida hacia arriba debido a que no se toma en cuenta la velocidad de sedimentación de las partículas. Se presentan también las medias mensuales de la sección latitud-longitud de la tasa de extinción, que muestran considerable heterogeneidad. Se utilizó un código de dispersión radiativa múltiple para valorar las tasas de calentamiento introducidas por un 75 % de aerosol de ácido sulfúrico. En el primer mes se predijo un aumento de hasta 2^{o} en la temperatura.

ABSTRACT

We have used the three dimensional circulation model of the stratosphere developed at MIT-GIT, to study the global dispersion of the volcanic cloud from the El Chichón eruption. The time dependent model is run for four months up to the end of October 1982. Initialization is provided through the measured latitude-altitude distribution of aerosol. Comparison of the results with experimental data made at days 105 and 120 from the beginning of the simulation shows a reasonable agreement although the concentrations resulting from the model are shifted upward because the sedimentation velocity of the particles is ignored. Monthly means of the latitude-longitude section of the extinction ratio are also presented showing considerable inhomogeneity. A multiple scattering radiative code has been used to evaluate heating rates introduced by a 75 % sulfuric acid aerosol. In the first month a temperature increase up to 2^{o} was predicted.

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INTRODUCTION

Large volcanic eruptions may inject considerable amount of dust in the stratosphere. The effect of this perturbation in the turbidity of the atmosphere is twofold: a decrease of the solar radiation reaching the ground and a local stratospheric heating due to absorption of both solar and possibly planetary radiation. Magnitude of these two effects depends mainly on the total optical thickness and the aerosol composition. General reviews on these arguments are those of Pollack *et al.* (1976) and Hansen *et al.* (1980). While detailed calculations on specific events are those of Hansen *et al.* (1978) and Pollack and Ackerman (1983).

Critical in the evaluation of the geographical extension of these effects is the knowledge of the production and transport of the particulate material. In large volcanic eruptions most of the aerosol may be produced directly from the sulfur gases injected in the stratosphere.

Pioneering work in this direction has been reported by Cadle *et al.* (1976) that studied dispersion of eruption clouds with a two-dimensional model. For the last two major volcanic eruptions (Mt. St. Helens in 1980 and El Chichón, in 1982) extensive data have been gathered so that more sophisticated modeling approach could be used to study production and transport. This need has produced results based on both one-dimensional modeling (Turco *et al.*, 1983), to study mainly the microphysics, and two-dimensional modeling (Pitari and Visconti, 1980, Capone *et al.*, 1983). Those two-dimensional efforts suffer from the basic flaws common to those models, namely a rather empirical way to solve the eddy transport. The approximations used are particularly weak in the case of typical sporadic events like volcanic clouds. Most of the transport fields for two-dimensional models refer to averaged seasonal quantities.

In this paper we present a quite different approach to the problem using a three-dimensional spectral model to predict the mixing ratio of dust after the production process has most likely ended. The three dimensional model uses precalculated fields for the vorticities and vertical velocities so that no interaction is supposed to occur between dust (through heating) and circulation. The dust is considered in this case to be a complete inert tracer, and for this reason we will refer to this approach as a 3D tracer model.

In the first part of the paper a brief description of the model is given together with a discussion of the basic assumptions we made. Results will be presented as zonal averages and will be compared directly with lidar data. Some results will also be presented as a function of latitude and longitude at a particular level to show the relationship with the geopotential field and the validity of attempted correlations between different stations.

Finally a simple radiative code is used to evaluate the expected heating rates introduced by the cloud and results will be discussed as function of latitude and altitude.

DESCRIPTION OF THE MODEL

a) Dynamics

For the dust, considered as a tracer, the model predicts the mixing ratio, χ, according to the equation:

$$\frac{\partial \chi}{\partial t} = -\vec{k} \times \nabla\psi \cdot \nabla\chi - W\frac{\partial \bar{\chi}}{\partial Z} + \frac{1}{H_0^2 P}\frac{\partial}{\partial Z}\left(K_d P \frac{\partial \chi}{\partial Z}\right) \tag{1}$$

In this equation variables are as follows:

χ = dust mixing ratio

ψ = streamfunction for horizontal velocity

W = "vertical velocity" = dZ/dt

Z = vertical log-pressure coordinate = $-\ln P$

P = pressure ÷ 1000 mb

H_0 = average stratospheric scale height

K_d = vertical diffusion coefficient

The overbar denotes horizontal average for each vertical level. Eq.(1) can be solved when zonal and eddy components of ψ and W are assigned. These dynamical fields are obtained from a run of the MIT-GIT 3D General Circulation model of the stratosphere (Cunnold *et al.*, 1975). Fig. 1 and 2 show respectively mean zonal winds and mean meridional circulation for season 1 (winter in the northern hemisphere and summer in the southern hemisphere) and season 2 (spring in the northern hemisphere and fall in the southern hemisphere).

The model includes 26 pressure levels which cover the altitude range between ground and about 70 km. For further details on the vertical resolution refer to the original paper of Cunnold *et al.* (1975). Truncated series of spherical harmonics $P_n^l(\mu)\exp(il\lambda)$ are used to represent various fields at all levels:

$$\psi(t, \lambda, \mu, Z_j) = \sum_{n=1}^{N_l} \sum_{l=-L}^{L} \Psi_n^l(t, Z_j)\, P_n^l(\mu) e^{il\lambda} \tag{2}$$

where λ and μ are longitude and sine of latitude. The truncation used is of romboidal type with L = 6; N_l is equal to 6, 7, 8, 9, 10 and 11 for $|l| = 0, 1, 2, 3, 4,$

5 and 6. This provides 79 degrees of freedom in each variable at each vertical level. The spectral method applied to solve Eq.(1) for isolated disturbances could present some difficulties related to the remote influence problem (Merilees and Orszag, 1979). We should expect a similar problem because, at the least initially, we are dealing with a dust cloud. The remote influence process consists in a spurious growth of any initial little noise on the grid space outside the region occupied by

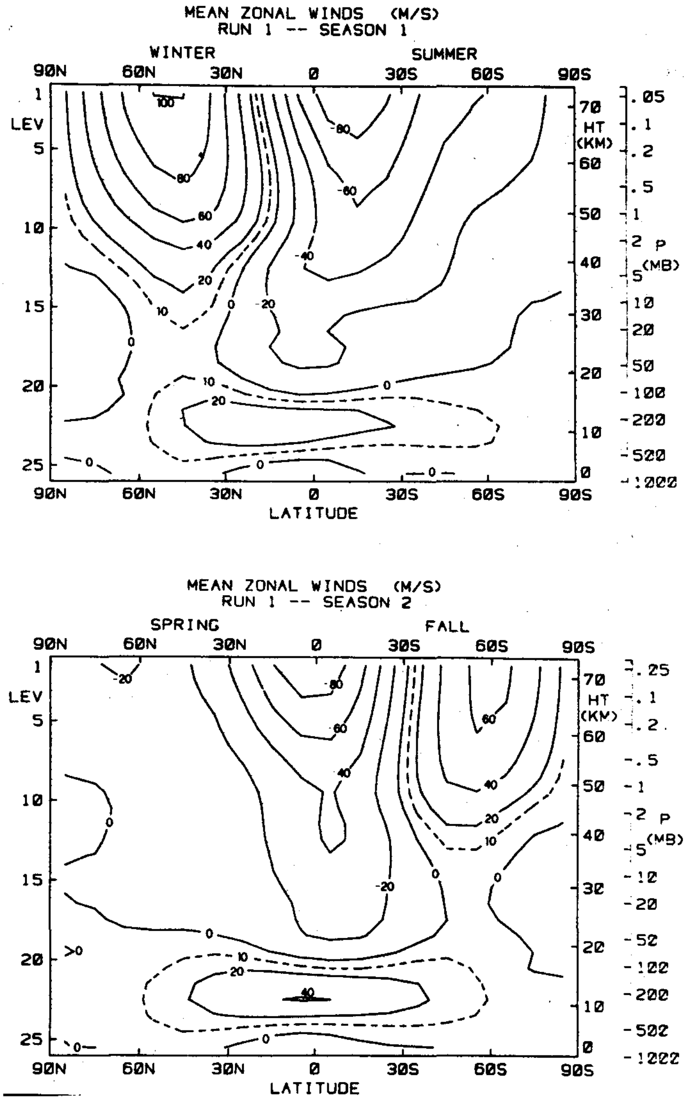

Fig. 1. Mean zonal winds for season 1 (winter-north, summer-south) and season 2 (spring-north, fall-south).

the aerosol cloud. This problem could be solved by using an adequate high spectral resolution, and actually the noise will be zero only for an infinite number of spectral components.

This remote influence can be controlled by making periodically a zonal average of the dust mixing ratio, removing the amount of aerosol outside the boundaries of the cloud, saving the total mass at each vertical level. This operation can be performed in our numerical model by simply maintaining unchanged the X_0^0 component (i.e. the horizontal average of χ at each vertical level) and re-evaluating the other zonal components by a full transform from a "modified" spatial grid, where χ is set to zero everywhere, except inside the cloud. The cloud boundaries can be identified by the first zero or negative value of χ at both sides from the center, at each vertical level.

This scheme however does not work satisfactorily with the six wave romboidal truncation mentioned above. This is because the resolution is not high enough to give a detailed representation of the initial stage of the cloud. Also the low resolution makes difficult to identify the boundaries of the cloud.

For these reasons the spectral representation was changed to an 18 wave triangular truncation scheme. The dynamic fields, that is ψ and W, remained the same of the original model.

Most of the computational time is devoted to the evaluation of the non-linear term $\vec{k} \times \nabla\psi \cdot \nabla\chi$; the procedure used is the so called full transform method, which is much faster than the interaction coefficient method when a large number of components is used.

The vertical advection term is computed using $\bar{\chi}$ to maintain consistency with the non-divergent character of $\vec{k} \times \nabla\psi$. For the prediction of the horizontal average $\bar{\chi}$ the vertical advection term (V.A.) becomes

$$\text{V. A.} = -\frac{1}{P}\frac{\partial}{\partial Z}\left[P(\overline{W'\chi'})\right] \tag{3}$$

where the primes denote a deviation from the horizontal average.

Prediction in time is performed using the "4 - cycle" version of the numerical differencing scheme given by Lorenz (1964).

b) The radiative transfer code

Heating introduced by the volcanic dust is calculated using a delta-Eddington radiative transfer code (Joseph *et al.*, 1976). The altitude range between the ground and about 42km is divided in 16 layers and for each of them an equivalent optical depth (τ), asymmetry factor (g), and single scattering albedo (ω) are given. These are determined by the presence of dust and other absorbing gases like oxygen and ozone. Ozone densities are assigned as a function of latitude and season. The spectral range between 0.22 and 7μ is divided in 51 intervals of variable width. The

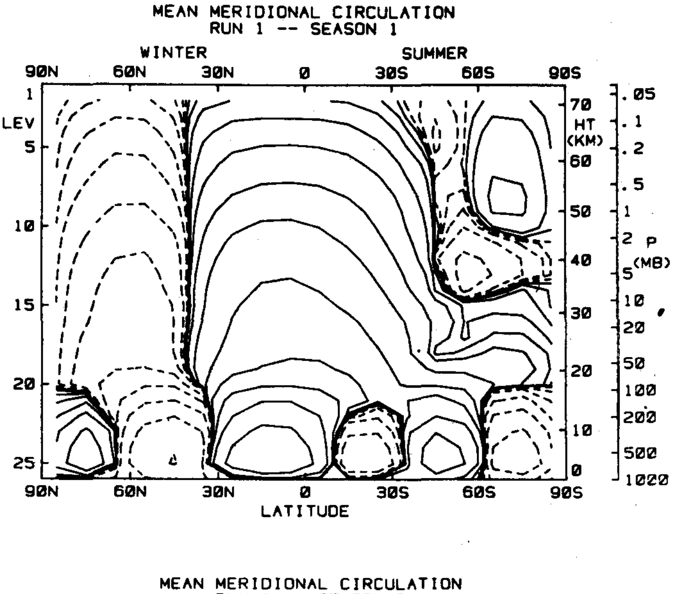

Fig. 2. Mean meridional circulation for season 1 and season 2. Solid line is for positive values of the mass streamfunction (northward transport in the upper part of each cell), dashed line is for negative values of the mass streamfunction (southward transport in the upper part of each cell).

scattering parameters which characterize each layer are also function of wavelength. Diurnal averaging is performed using an empirical method (D. M. Cunnold, Personal Communication) based on a weighted average on two solar zenith angles. A separate Mie scattering program is used to evaluate ω, g and Q_{ext} (extinction cross section) for the aerosols. More details of this code can be found in Visconti (1981).

INITIALIZATION AND BOUNDARY CONDITIONS

Our experiment has been started on July 1st, which means about three months after the eruption of El Chichón. The initial distribution of dust was obtained from data reported by Labitzke *et al.* (1983). These data refer to backscattering profiles at different latitudes, taken with an airborne lidar. They span latitude between 35°N and 13°N, and were taken between July 9 and 11. Data are lacking below 13°N and in the southern hemisphere. Lidar data are more simple to interpret than some reported data from satellite. They give directly the altitude distribution, however the backscattering profiles do require some additional handling to obtain the mixing ratio of dust. We have followed the method outlined by Russell *et al.* 1981a, b). A very important parameter in this approach is the concentration ratio between particles with $r > 0.15$ and 0.25μ. For this purpose we have used the data presented by Hofmann and Rosen (1983a) which do refer to some later time and to narrower range of altitude. As shown in a subsequent paper (Hofmann and Rosen, 1983b) this may be not a good assumption because the size distribution may change during the first 6 months after the eruption. In this preliminary work however we are mainly interested in assessing the transport characteristic of the dust so that we only need a rough approximation of the dust mixing ratio. Also the limited resolution of the spectral method implies in any case a certain amount of smoothing of the initial data. To check our estimation of the mixing ratio we compared our results with those reported by Hofmann and Rosen (1983a) and made an independent determination using the method illustrated by Pinnick *et al.* (1980) by using an exact estimation of the Q_{ext} to mass ratio.

Several other approximations were included in our initial conditions; the more critical are the assumption of the rough symmetrical distribution in latitude to fill the gap below 13°N and the assumption of zonal uniformity in dust mixing ratio. Very few data exist for southern latitude in particular those of Clemesha and Simonich (1983) which are lidar data taken at 25°S. They show that in July the dust loading at that latitude was still quite small which would confirm our assumption of a limited spread to the southern latitude at this time.

The assumption of a mixing ratio independent of longitude is subject to some criticism. Transport times in longitude are shorter than those in latitude. However, some of our results do show that even after several months from the eruption the distribution is uniform only in a very limited range of latitude.

On the other hand very limited data exist in this direction except those which refer to very low altitude cloud (Krueger, 1983; Robock and Matson, 1983). A later work will consider this aspect in more detail especially for the implication it could have on the correlation attempts between differently located ground stations.

As mentioned in the model description this particular run neglects the effect of the settling velocity. In that it follows the same assumption of Cadle *et al.* (1976). This approximation will affect the vertical distribution of dust but should not imply important consequences on the latitudinal transport time.

The limited amount of computer time also restricted the altitude range considered between roughly 9 and 42 km. At those boundaries we assumed zero flux for both the eddy ($\overline{W'\chi'}$) and diffusive flux ($k_d \partial\chi/\partial Z$). These boundary conditions may be consistent with the assumption of constant aerosol total mass, but may not represent the real physical situation especially if sedimentation velocity is considered.

An important assumption of this experiment is that we do not model production of aerosol from heterogeneous processes or reactions. This correspond to assume that after 3 months all the dust production has stopped and no phase change occurs for the aerosol particles thereafter.

Only very recent analytical work deals with aerosol growth in a volcanic cloud (Turco *et al.*, 1983). The experimental evidence in the specific case of El Chichón eruption (Hofmann and Rosen, 1983b) seems to point out to a continuous growth six months after the eruption. This assumption here reflects our interest on the transport processes of a simple tracer in order to assess separately also the influence of photochemical processes in determining the latitudinal distribution of dust.

The radiative properties of the dust needed to evaluate the heating rates were calculated with a Mie scattering program whose input was a sulfuric acid aerosol with 75% H_2SO_4 concentration. No silicate component was considered in this calculation and the optical constants for sulfuric acid were those of Palmer and Williams (1975). A silicate component was measured by Patterson (1983) in the El Chichón volcanic ash. However, we think its consideration would not change much our results. We used a Zold size distribution with maximum radius $r_M = 0.15$ and $\sigma = 1.9$.

In this experiment we considered dust to interact radiatively only with solar radiation. This means that we do not consider IR effects due to dust itself or interaction with planetary radiation. Surface albedo was 0.1 and no clouds were assumed to be present in the troposphere while the absorption of water vapor in the same region was taken into account.

Recent work by Pollack and Ackermann (1983) shows that infrared radiation transfer could be important in determining heating rates. As consequence our future work aimed at considering interactive experiments must take into account IR effects to asses the dust heating feedback on the circulation.

RESULTS AND DISCUSSION

a) Dust transport

Our results for the dust distribution are plotted as extinction mixing ratio (Russell *et al.*, 1981b). This is actually the lidar backscattering ratio minus 1. The reason is that the only data we could compare with our results are those taken with an airborne lidar (M. P. McCormick, personal communication). Fig. 3 shows zonal aver-

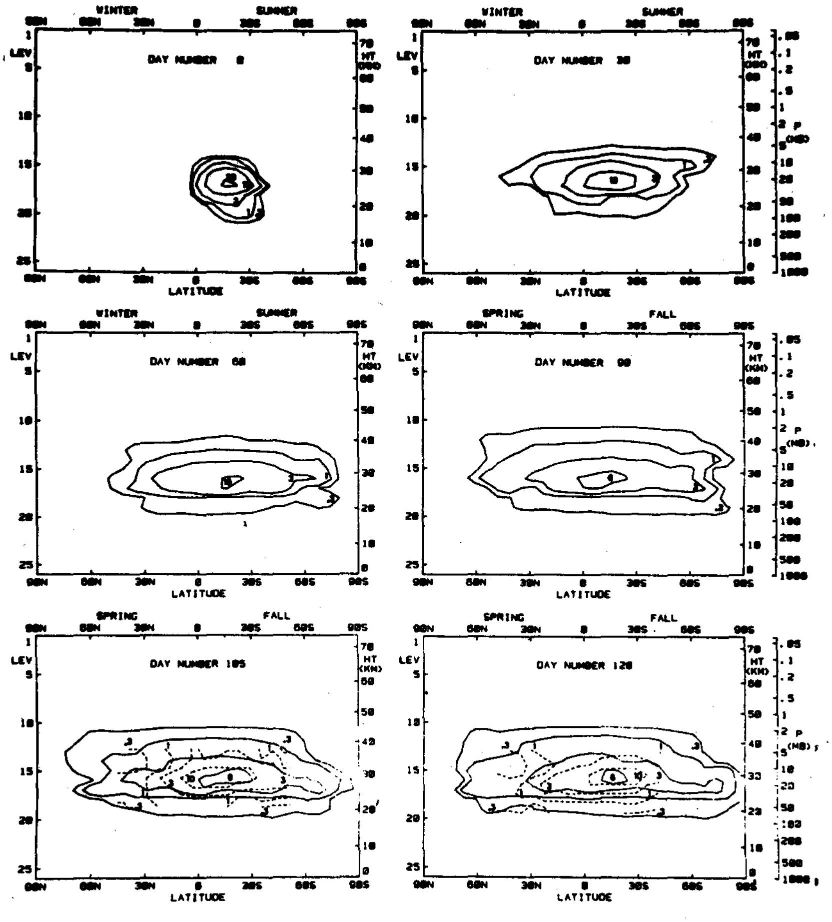

Fig. 3. Mean zonal values of aerosol extinction mixing ratios from July 1st to October 30th. Dashed line refer to airborne lidar experimental results (McCormick, personal communication).

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ages of the extinction mixing ratio as a function of time after the beginning of the experiment. Day 0 would actually correspond to July 1st and so it is about 3 months after the eruption. Data shown for day 0 suffer from the smoothing problem we mentioned earlier. Also the actual computer run was made using mass mixing ratio. The conversion of the initial backscattering ratio to mass mixing ratio would also imply the same kind of grid averaging which also reduce the peak values with respect to the really observed distribution. For these reasons while the original data shows peaks greater than 40, our maximum values are somewhat higher than 30.

These and subsequent figures require some clarifications. The suscript "RUN 1" refers to the GCM "preliminary run". We remember that in this model the two hemispheres are symmetric in the sense that topography and equilibrium temperature for tropospheric heating computation refers to the north hemisphere. The subscript "RUN 2" refers to the aerosol final run; for symmetry with the dynamics results, we have plotted w nter and spring hemispheres on the left, summer and fall hemispheres on the right. For this reason and for the hemisphere symmetry the cloud center appears on the pseudo-south model hemisphere. For consistency we have also redrawn the experimental data.

According to our calculations, dust reached mid-latitudes already in August with average extinction ratio around 2 at an altitude around 30 km. Lidar measurements taken during this period at these latitudes do show very high altitude layers (D'Altorio and Visconti, 1983) with peak mixing ratio much higher than those reported here. We will see however some effects of this kind could be introduced by the inhomogeneity in longitude. During September and October most of the dust seems to be arriving at mid and northern latitudes in the altitude range between 20 and 30km. However, in October there is a definite downward shift due to changing fall circulation. In all our plots dust seems to be in the southern hemisphere. As we mentioned earlier the model is completely symmetric so that this has to be regarded as summer and fall in the Northern hemisphere. The last two graphs in Fig. 3 show a comparison with the lidar data (M. P. McCormick, personal communication) averaged over October 19 - 29 and October 29 - November 4. In these figures the experimental data are shifted upward by something more than 4km at day 105 and about 5km at day 120. This was made just for the sake of clarity but it points out a rather serious inadequacy of the model, which is probably due to the fact we neglect the sedimentation velocity of the particles. Actually during the experiment the region of maximum concentration shifts upward, which is consistent with the mass circulation given in Fig. 2. If we take the average sedimentation velocity of 0.15μ particles as representative, at 30km it has a value of about 0.03 cms^{-1} and 0.015 cms^{-1} at 25km. In 105 days this would give a shift between 1.3 and 2.7 km, while in four months the shift would be about 300m greater. Another effect to be considered is due to the condition at the upper boundary. The zero flux condition there, implies a spurious accumulation of dust at the upper level, this contributing to shift upward all the dust distribution.

With those arguments we expect the experimental values to be reproduced more closely. Unfortunately we had no time to test such modifications with an actual computer run. Fig. 4 shows the mass columnar density as a function of latitude at the beginning of the experiment and four months later. Initial distribution is rather symmetric and it is centered around 15^{o} latitude. After four months the distribution shows probably more dust in the fall hemisphere and also too much in the

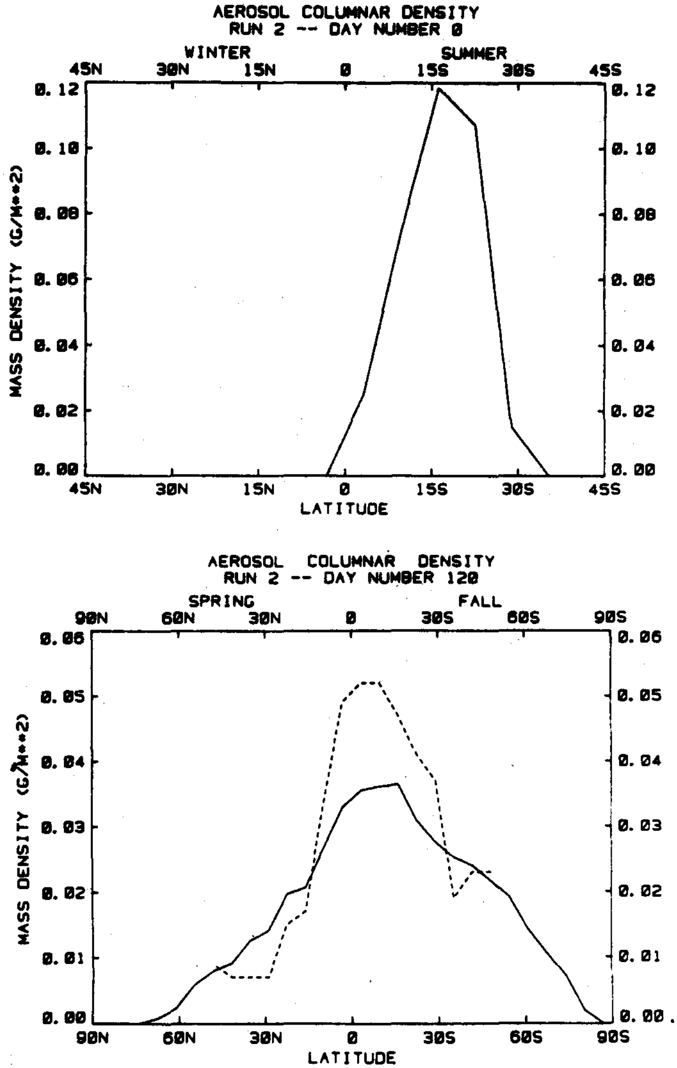

Fig. 4. Aerosol total mass columnar density at July 1st and October 30th. Dashed line refers to McCormick and Swissler (1983) experimental results.

spring hemisphere, as compared to the experimental data. Also the smoothing process is here evident with the peak mass density of the experimental data being 15% higher than the results of the model.

We will discuss now some of the results concerning the homogeneity in the zonal direction. Fig. 5 shows two plots of extinction mixing ratio at about 25km for summer and fall. These are monthly averages. From these figures we see that the assumption of dust mixing ratio independent of longitude is only valid for latitude circles near the equator. In the winter hemisphere the inhomogeneity is more pronounced that in the summer hemisphere reflecting a more intense wave activity. It is to be considered that these are monthly means so that the anomalies shown here

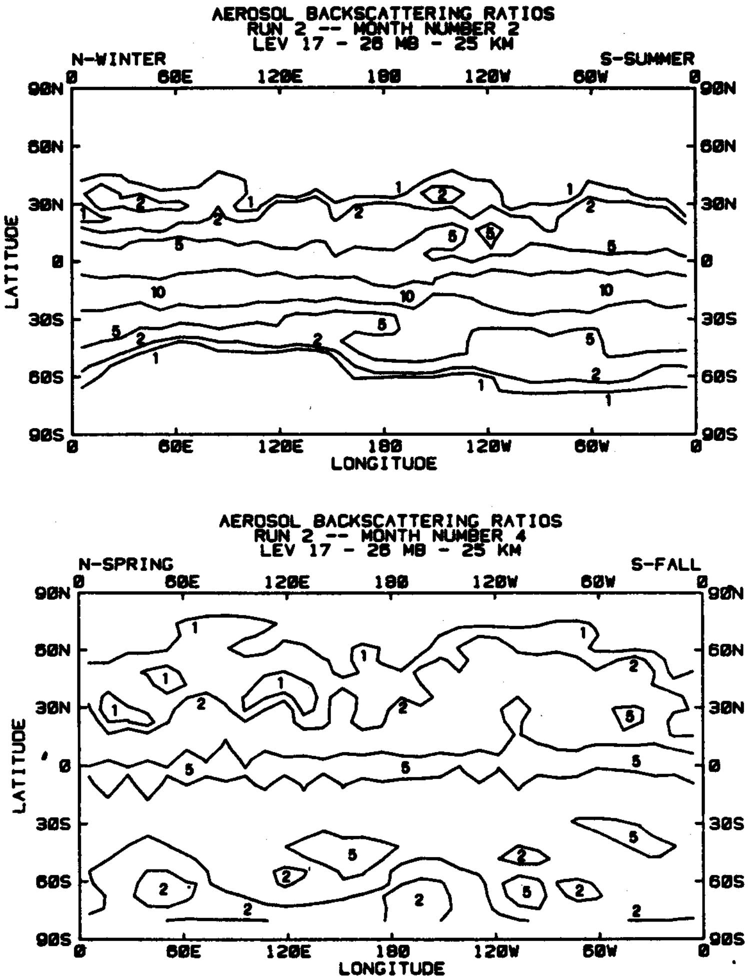

Fig. 5. Latitude vs. longitude aerosol extinction mixing ratios for August and October at an approximate height of 25 km. For a misprint the caption on the figure is aerosol backscattering ratios.

should be reasonably constant in the position shown. Particular resemblance is shown between these results and similar plots reported in Cunnold *et al.* (1975) for the geopotential height at 10mb.

This longitudinal inhomogeneity deserves further analysis especially on a time dependent basis. However, these preliminary results show that correlation between different ground stations and attempts to infer stratospheric circulation pattern from the signal observed at few stations must be carried out with some caution.

b) Dust heating rates

Our final results deal with heating rates as shown in Fig. 6, for the aerosol distributions shown in Fig. 3. This results seem to be consistent with both earlier re-

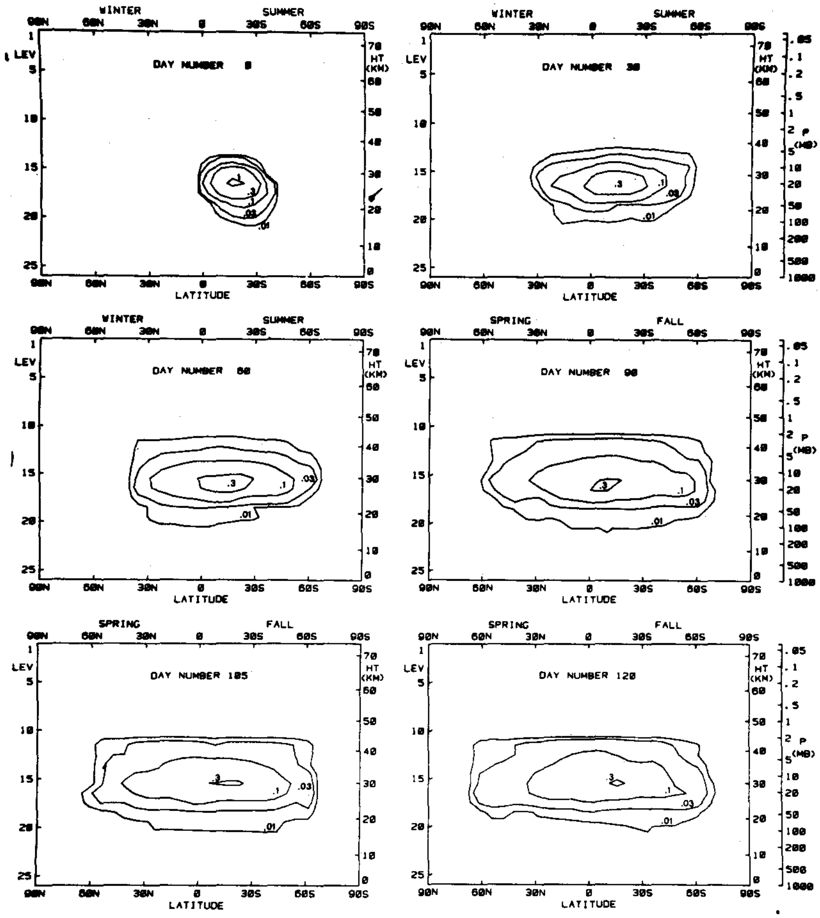

Fig. 6. Mean zonal values of aerosol heating rates from July 1st to October 30th. These heating rates were calculated taking into account only dust interaction with solar radiation, and are averaged diurnally. Units used are 0.1 degrees per day (i.e. 1 on the plots means 1 x 0.1 = 0.1 degrees/day).

sults by Pollack *et al.* (1976) and more recent calculations by Pollack and Ackerman (1983) or Patterson *et al.* (1983). Our results show that for the initial optical depth of about 0.28, the heating ratio is of the order of 0.12 deg/day at 26km. Considering a newtonian cooling coefficient of 0.06 day^{-1} at the same altitude we would obtain a temperature increase of about 2^o. This value is somewhat smaller with respect to those reported by Pollack and Ackerman (1983). However, they also show that IR effects and the ash fraction could be of some importance. On the other hand preliminary results on the stratospheric heating introduced by the El Chichón dust (Labitzke *et al.* 1983) are subject to further discussion (Quiroz, 1983).

CONCLUSIONS

A three-dimensional tracer circulation model has been used to study transport of the volcanic aerosols produced by the El Chichón eruption. The model uses precalculated values of the vorticity and vertical velocity derived from a specific run of a 3D stratospheric circulation model (Cunnold *et al.*, 1975). Initialization of the model utilizes lidar data taken at the beginning of July, 1982. The model itself is run fromJuly 1st to October 30th. Basic assumptions of the model are to consider the dust as a complete passive tracer with production or reevaporation ending by July 1st. Sedimentation velocity is also ignored. Results are compared at day 105 and 120 with lidar data. It is found that due to the neglect of sedimentation velocity the model cloud is shifted upward by an amount consistent with that assumtion. Columnar mass density as a function of latitude gives a smaller dust load at tropical latitudes compared to experimental data and apparently a faster transport to mid-high latitudes. These effects could be attributed to both the smoothing introduced by the 3D spectral model and also to the fact that production of aerosol from the gas in the tropical regions is continuing after July 1st. Latitude-longitude monthly means of the extinction ratio at a fixed altitude are also presented and they show some very interesting results. The initial condition was to assume the dust distribution to be completely uniform in longitude. Our results for two different seasons (late summer and fall) show considerable inhomogeneity. Dust distribution however at 26mb show some correlations with the geopotential map at the same altitude, with a rather uniform distribution near the equator or in the summer hemisphere. Wave activity being more intense in winter, spring and fall is responsible of the observed inhomogeneity. Because the extinction ratio features are averaged over one month they should have some degree of standing character over the different geographical regions. This effect should make more difficult to correlate ground measurements taken at different geographical sites or with the stratospheric wind circulation.

A delta-Eddington radiative transfer code is also used to compute heating rates introduced by the aerosols. A 75% sulfuric acid aerosol is considered and detailed calculations based on the appropriate Newtonian cooling coefficient show temperature increase of about 2° at 25 km. This is somewhat smaller than those presented by other studies and emphasizes the possible role of IR transfer or ash impurities in determining the local warming.

In conclusion results from this preliminary experiment show that horizontal advection is the main mechanism affecting the evolution of meridional distribution of dust with time, at the least after the first few months from the eruption.

The model results however underestimate dust concentration at tropical latitudes indicating that dust production takes place well after the beginning of our experiment. On the other hand gravitational settling is an important parameter in determining the altitude distribution of the dust. Some results from more recent runs of the same model including the deposition velocity are able to discriminate about the size of the particles.

The results also show a pronounced inhomogeneity in longitude which makes less obvious to correlate the observations at the ground with the zonal winds.

The heating introduced by the dust also must take into account both IR effects and an ash component in the particles.

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