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PRELIMINARY ESTIMATE OF THE RADIATIVE AND CLIMATIC EFFECTS OF THE EL CHICHON ERUPTION

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RESUMEN

Se hizo una estimación preliminar del efecto climático de la mayor erupción volcánica de El Chichón en abril de 1982, utilizando una versión estacional de un modelo zonal de clima, considerando una capa oceánica de 70 m . El aerosol volcánico se introdujo en el modelo de estratosfera a una altitud de 23 - 29 km, donde el aerosol perturba ambos flujos, el solar y el infrarrojo. Se consideró una composición de aerosol de 75% de H_2SO_4 con una distribución logarítmica de tamaños de orden cero. Se utilizó el patrón de opacidad latitudinal y variación temporal desarrollado por Robock (1983), con el pico de opacidad alcanzando 0.3 en junio de 1982. En este cálculo, el caso de perturbación volcánica se corrió desde el 1o. de abril de 1982 hasta el 1o. de enero de 1983. La temperatura del hemisferio norte se proyectó a decrecimiento gradual durante este período, siendo alrededor de 0.2 K más fresca que lo normal a fines de 1982. El modelo predice también anomalías en la precipitación, incluyendo una reducción de cinco a más de diez por ciento en la tasa de precipitación exactamente al norte del ITCZ.

ABSTRACT

A preliminary estimate of the climatic effect the major El Chichón volcanic eruption of April 1982 has been made using a seasonal version of a zonal climate model with a 70 m slab ocean. The volcanic aerosol was introduced into the model stratosphere at a height of 23 - 29 km where the aerosol perturbs both the solar and infrared fluxes. An aerosol composition of 75% H_2SO_4 with a zero-order logarithmic size distribution is assumed. The latitudinal and time-varying pattern of opacity developed by Robock (1983) is used, with the peak opacity reaching 0.3 in June 1982. The volcanically perturbed case is run from April 1, 1982 to January 1, 1983 in this calculation. The Northern Hemisphere temperature is projected to gradually decrease during this period, being about 0.2 K cooler than normal at the end of 1982. The model also predicts precipitation anomalies, including a reduction of five to more than ten percent in precipitation rate just north of the ITCZ.

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1. INTRODUCTION

The injection of dust and sulfur oxides into the stratosphere by the April 1982 eruption of the El Chichón volcano located in southeastern Mexico has led to significant perturbations of visible (solar) fluxes of radiation (DeLuisi *et al.*, 1982). These perturbations greatly exceed those of any volcanic eruption of at least the last 20 years and, in the Northern Hemisphere, perhaps since the beginning of this century. As such, the El Chichón eruption provides the opportunity for interfacing observational and analysis studies in the expectation of improving our understanding of the climate and its sensitivity to alterations of radiative processes.

Because the driving force for climatic effects is the direct radiative forcing, detailed radiative calculations have been performed to examine the dependencies of flux perturbations on particle composition and size distribution. An approximation to the detailed radiative forcing has been included in a zonal statistical dynamic climate model to calculate the seasonal climatic response to the volcanic aerosol.

Climate model results indicate that the global temperature gradually decreases during the first year, in good agreement with simpler energy balance model results (Robock, 1983). In addition, however, changes are induced in the zonal pattern of precipitation. Such changes, not previously examined or measured, may be the most interesting climatic effect to examine as observations become available, especially if, as seems possible, feedbacks exist between the time and space dependence of the radiative forcing and the climatic response.

2. RADIATIVE EFFECTS OF EL CHICHON

While the El Chichón eruption released about the same amount of dust as the eruption of Mount St. Helens in May 1980, the material from El Chichón was lofted into the stratosphere rather than into the troposphere (see Newell and Deepak, 1982; Self, 1982). And unlike Mount St. Helens, El Chichón also released a large cloud of sulfur-containing gases that stabilized at altitudes between 22 and 28 km (Coulson *et al.*, 1982). At these altitudes there is very little vertical motion of the air, so there is time for the sulfur-containing gases to be converted to sulfuric acid droplets through chemical conversion.

These sulfuric acid droplets are very effective scatterers of sunlight, causing normally blue skies to appear milky during the day with vivid sunrises and sunsets. Measurements made at Mauna Loa Observatory, which is at approximately the same latitude as El Chichón, and elsewhere indicate that significant reductions in direct radiation and increases in scattered (diffuse) radiation occurred subsequent to the eruption and coincident with lidar measurements indicating the presence of a high-altitude aerosol layer (Coulson *et al.*, 1982).

Because the aerosol cloud stabilized at such high altitudes, direct sampling of the particles has been difficult. Aircraft flights that reached a maximum altitude of 20 km sampled the aerosol in the lower stratosphere, but the main stratospheric cloud was above this altitude (Mroz and Sedlacek, 1982; Woods and Chuan, 1982). The stratospheric cloud was determined to consist of sulfuric acid droplets with very small amounts of volcanic ash (Harder *et al.*, 1983). The particle size distribution was determined to have a mean mode radius of 0.3 μm (De Luisi *et al.*, 1982; Harder *et al.*, 1983). Spectral measurements of optical depth showed a relatively flat distribution through the visible spectrum with a peak optical depth at 0.55 μm (DeLuisi *et al.*, 1982). The spectral distribution remained relatively constant (although varying in magnitude) throughout the measurement period (until early 1983), indicating little change in the particle size distribution.

Using a detailed radiative transfer model (Braslau and Dave, 1973), we calculated the spectral distribution of optical depth assuming the aerosol to be 75% H_2SO_4 and 25% H_2O. A zero-order logarithmic size distribution was assumed, and values of $r_m = 0.30\mu m$ and $\sigma = 1.35$ gave the best fit to the spectral optical depth measurements for July 1982.

The calculated effects of the stratospheric aerosols on direct and diffuse solar flux components are shown in Table 1. The optical depth at 0.55 μm is assumed to be 0.255, which was observed in July 1982 in Hawaii (Coulson *et al.*, 1982). Although the direct solar flux is reduced significantly (up to 30%), the scattering is primarily in the forward direction, so the increase in the downward diffuse component compensates for most of the reduction in direct radiation. These results are in good agreement with measurements taken at Mauna Loa Observatory (K. Coulson, private communication, 1982).

Table 1

Clear-sky solar radiative effects at the surface calculated for an aerosol layer with optical depth 0.255

Quantity	Solar zenith angle 30°	60°
Change in direct flux	– 19%	– 30%
Ratio of diffuse/direct:		
no aerosol	0.04	0.07
with aerosol	0.28	0.46
Change in total flux	– 1.2%	– 4.9%

The radiative properties of the aerosol cloud (transmissivity and reflectivity at the top and bottom of the layer and the effective cloud fraction) were computed for several solar zenith angles and parameterized for inclusion in the climate model. The particle size distribution was assumed to be constant in time. In our preliminary calculations the aerosol layer was treated as a blackbody in the longwave spectrum with a broad-band optical depth 5.9% of the visible optical depth. Based on Harshvardhan and Cess (1976), the absorptance by the aerosol layer of upward longwave flux is increased by a factor of 1.26 to account for the fact that the spectral distribution of upward flux differs from that of blackbody emission.

3. CLIMATIC EFFECTS OF EL CHICHON

3.1 *Statistical-Dynamic Climatic Model*

The LLNL Statistic-Dynamical Model (LSDM) has been used to estimate the climatic effects of the El Chichón eruption. The LSDM is a zonal model having a 10^{o} grid extending from pole to pole with nine pressure layers extending vertically into the stratosphere (Potter *et al.*, 1979a; MacCracken *et al.*, 1981). The model is thus able to resolve the temporal evolution of the latitude and height distribution of the volcanic aerosol.

According to the classification scheme developed by Saltzman (1978) in his extensive review of climatic models, the LSDM is a II.B. (statistical-dynamic, momentum) model. The hydrostatic equation is used to determine surface pressure, and the primitive form of the conservation equations for thermal energy, water vapor and meridional and zonal momentum are used to represent the zonally averaged mean flows of the atmosphere. The net effects of eddy motions are represented by incorporation of parameterizations. For eddy transport of heat and water vapor, a diffusion approximation is used with the vertical and latitudinal variations of the eddy diffusion coefficients based on parameterizations by Stone (1972, 1973), but including a baroclinic adjustment, if necessary (Stone, 1978). Because adequate approximation of the eddy momentum transport has proven difficult (Saltzman, 1978), zonal transport of eddy momentum at each latitude and height is prescribed based on a Fourier fit to the monthly observations compiled by Oort (1983).

At each latitude, up to five separate surface types (ocean, sea ice, sea level land, low mountains, and high mountains) are treated separately in terms of processes affecting the surface energy balance and atmospheric boundary layer, but are averaged together in treating processes involving latitudinal transport. The hydrologic cycle is represented at the surface by including a soil moisture "bucket" and treating build-up and melting of snow and ice cover based on the local surface energy and moisture balance. The ocean is represented by a well-mixed layer 70 m deep. Observed estimates of the meridional fluxes of heat by ocean currents are prescribed independent of atmospheric conditions; no provision is made for El Niño conditions.

The present, preliminary seasonal variation of the LSDM prescribes seasonal variation of the cloud amount at each latitude based on fits to the observations of Berlyand *et al.* (1980), with the vertical distribution of cloud cover by latitude based on fits to analyses based on the work of Rodgers (1967), London (1957), and Sasamori *et al.* (1972). The latitudinal, vertical, and seasonal distribution of ozone is also prescribed based on Nimbus 7 solar backscattered ultraviolet instrument observations of McPeters *et al.* (1983). Sea ice amount at each latitude is based on the local energy balance and an empirical fit relating fractional sea ice coverage to ocean temperature as a function of the ocean fraction at each latitude (MacCracken *et al.*, 1981).

Radiative calculations include consideration of water vapor, cloud cover, ozone, and aerosol amount in the solar and infrared spectral regions. Solar absorption by nitrogen dioxide and Rayleigh scattering in the visible spectrum are also included. Global energy balances indicate closer agreement with detailed radiation models than with estimates derived from observations (e.g., Sellers, 1965; NAS, 1975), the major difference being a lower planetary albedo (~0.3) and enhanced back-radiation to the surface from the atmosphere.

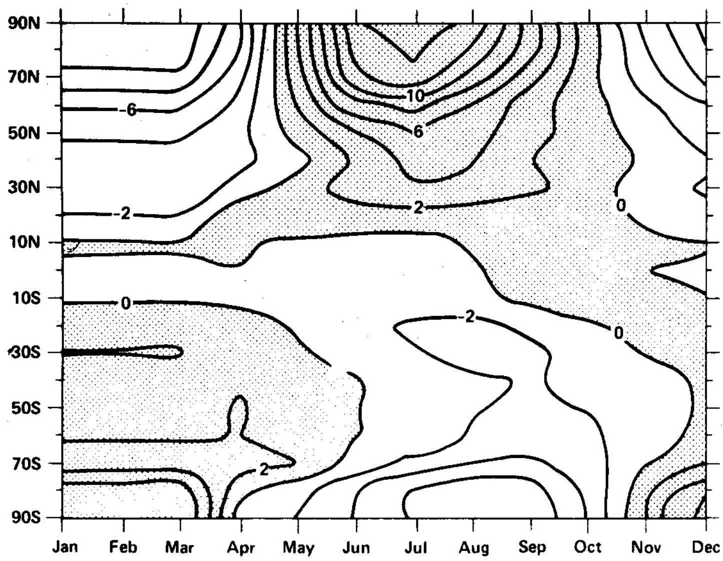

FIGURE 1a.

Fig. 1. Monthly variation in zonal average surface temperature (°C) about the annual mean: (a) calculated for 925-1000 mb level, (b) calculated for surface, (c) based on observations at 1000 mb from Crutcher and Meserve (1970) and Taljaard *et al.* (1969). The 925-1000 mb layer temperatures show somewhat less variation and surface temperatures somewhat greater variation than observations at 1000 mb.

The resulting simulation of the present seasonal cycle gives quite reasonable agreement with the phase and amplitude for surface temperatures and radiative fluxes, as shown in Figs. 1 and 2. The intertropical convergence zone also shifts latitudinally with the seasons, as indicated in Fig. 3 by the variation of precipitation about the mean. There does appear to be a lag in the response compared to observations, and the amplitude of the seasonal cycle is too small in the sub-tropics. The Southern Hemisphere rainfall cycle also appears not to be well represented.

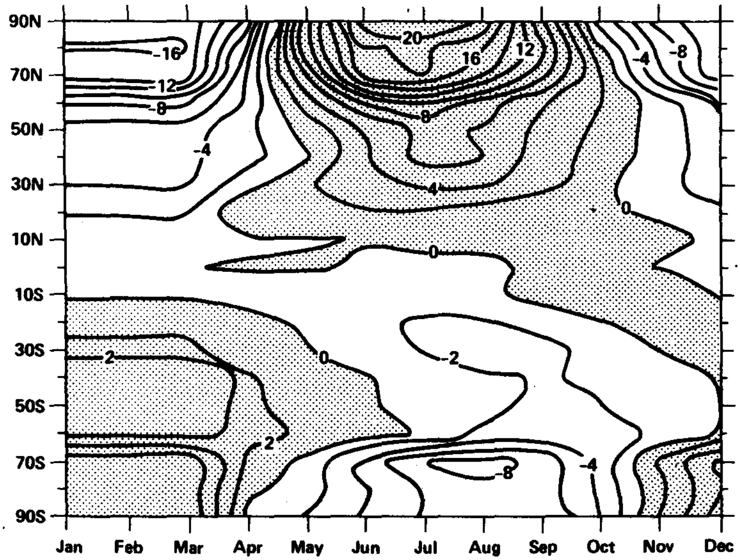

FIGURE 1b.

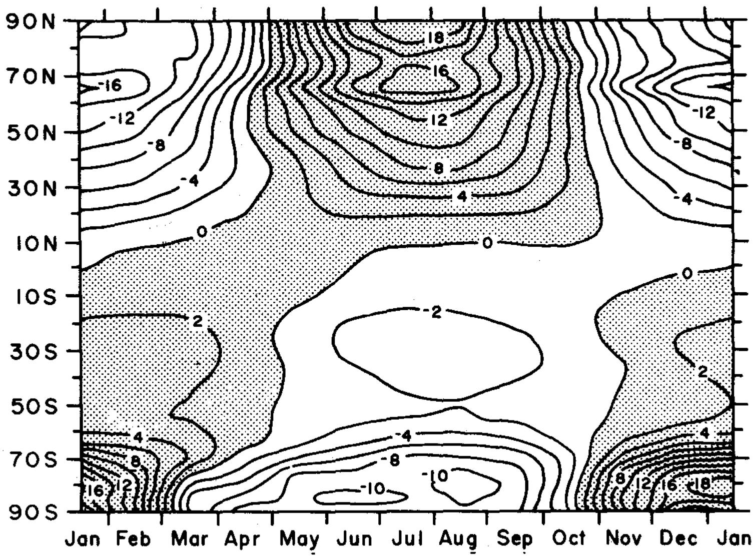

FIGURE 1c.

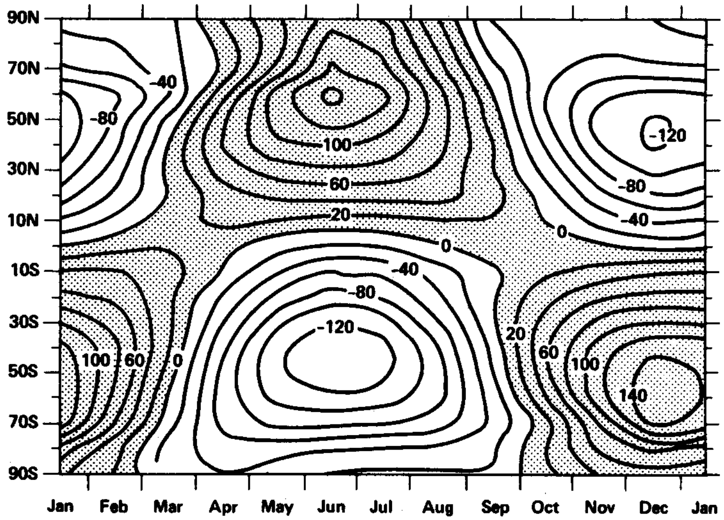

FIGURE 2a.

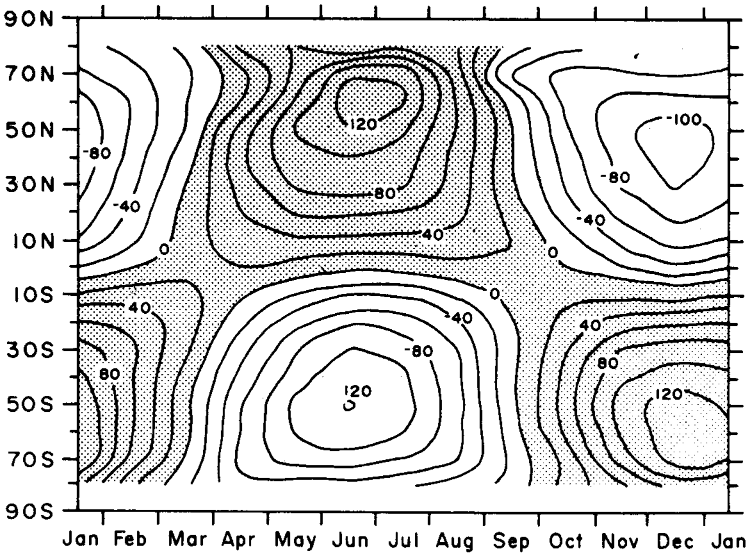

FIGURE 2b.

Fig. 2. Monthly variation in zonal average net radiation at the top of the atmosphere (W/m^2): (a) calculated, (b) based on observations from Stephens *et al.* (1981).

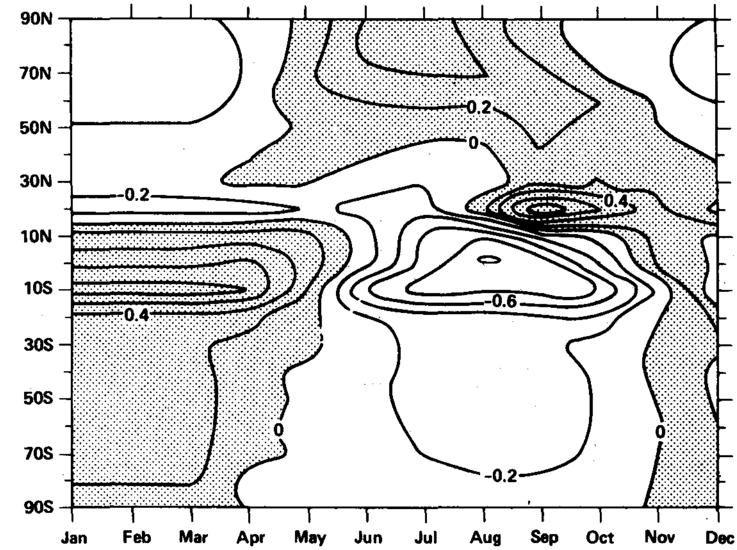

FIGURE 3a.

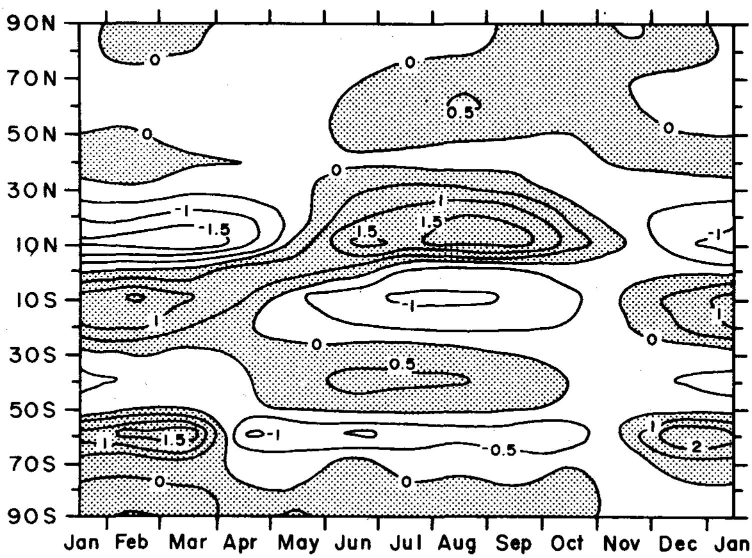

FIGURE 3b.

Fig. 3. Monthly variation in zonal average precipitation (mm/day): (a) calculated, (b) based on observations from Jaeger (1976).

Given present model performance, the LSDM offers several advantages over other types of models when applied to study of the El Chichón eruption. Compared to fast-running energy balance models (e.g., Robock, 1983), the LSDM includes a vertical structure that allows more complete treatment of radiative and hydrologic processes and permits the model to have a dynamic responsiveness that more accurately represents the degrees of freedom possessed by the Earth's climate system. While not able to represent the regional effects that may occur and can, at least theoretically, be identified in general circulation model (GCM) results, the LSDM does not suffer from the signal to noise difficulties inherent in GCMs because the details of synoptic motions are represented in a smooth, rather than turbulent, manner (i.e., via diffusion for heat and water vapor, and by a smooth fit to observations for momentum rather than by actual calculation of the baroclinic activity). Thus, the LSDM provides a bridge between the thought-provoking, but necessarily somewhat qualitative, insights available from energy balance models (EBMs) and the physically detailed, but sometimes undiscernible, results of GCM simulations. In this role, the LSDM can help to provide a fuller context in which to view the results of EBMs and to better target analyses of the more complete GCM simulations.

3.2 *Equilibrium Effects of the Initial El Chichón Injection*

In order to test the potential magnitude of the climate's response to the initial El Chichón injection and the climatic tendency to expect in later transient calculations, an annual average version of the LSDM was used (Potter *et al.*, 1979a, 1979b) assuming an aerosol cloud extending from 23 to 29 km in height and from 5°N to 35°N and having an optical depth of 0.255 at 0.55 μm. This is roughly equivalent

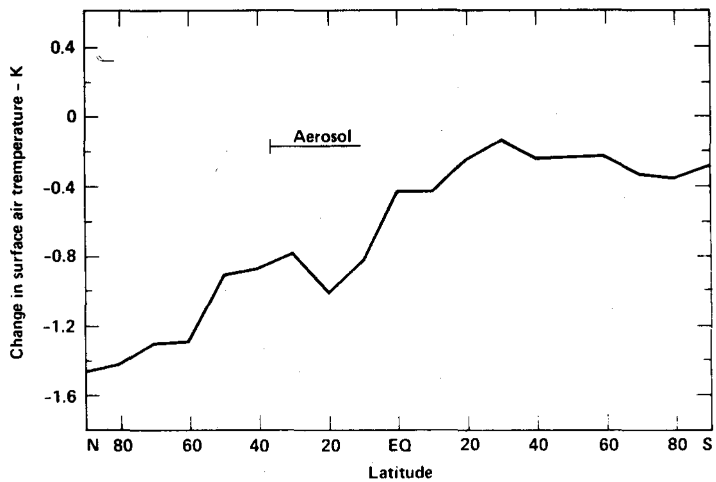

Fig. 4. Zonal average change in annual average surface temperature (°C) at equilibrium assuming a fixed increment to stratospheric optical depth of 0.255 extending from 5°N to 35°N.

to conditions in June 1982 before the aerosol cloud had begun spreading to other latitudes. At equilibrium, there was surface cooling in both hemispheres. The temperature decrease was about 1.0 K at 20°N and increased with latitude in the Northern Hemisphere to about 1.4 K at 70°N due to ice-albedo feedbacks at high latitudes, as shown in Fig. 4. The average decrease in surface air temperature was about 0.9 K in the Northern Hemisphere and 0.3 K in the Southern Hemisphere. The model also indicated a southward shift in the intertropical convergence zone (ITCZ) with a stronger Northern Hemisphere Hadley circulation that drew heat out of the Southern Hemisphere oceans and supplied it to the Northern Hemisphere subtropics, thereby sharing the radiative anomaly with that hemisphere even though no aerosol was assumed to be present in the Southern Hemisphere in this calculation. Because of this shift of the ITCZ, the Southern Hemisphere sub-tropics received more rainfall and the Northern Hemisphere sub-tropics somewhat less rainfall. These changes in turn were apparently amplified by surface albedo changes resulting from initial changes in soil moisture. The global hydrologic cycle became less intense with less evaporation and precipitation (with the greatest decrease under the aerosol layer), and with somewhat less total precipitable water.

This shift in the ITCZ is consistent with the results of Charney (1975) and Kutzbach and Otto-Bliesner (1982) who also considered perturbations, although from quite different causes, to the radiative fluxes in the Northern Hemisphere subtropics. Charney considered the case of desertification in the Sahel, which led to an increased surface albedo, a relative energy deficit, and a southward shift of the tropical rain belt so that descending air over the subtropics could compensate the radiative deficit. Ellsaesser *et al.* (1976) reported similar results with the LLNL two-dimensional model. Kutzbach and Otto-Bliesner considered the effect of orbital changes on the solar radiation reaching the Northern Hemisphere during the deglaciation phase 9 000 years ago. Their results indicated that the increase in summer radiation at that time led to an increased monsoonal circulation, its extent shifted northward across southern Asia. These results were found to be in agreement with Indian Ocean sediment data indicating current shifts consistent with an increased monsoonal circulation at that time. Taken together these results appear to indicate that the latitudinal position of tropical circulation and rainfall systems respond so as to tend to balance the thermal energy available to each hemisphere.

3.3 *Evolution of the El Chichón Aerosol Distribution*

The El Chichón aerosol, of course, will not remain constant, but will evolve in time. However, although measurements exist at a few locations indicating the spread of the aerosol from the time of its initial dispersion around the globe (Robock and Matson, 1983) through 1982 (McCormick, 1982; Spinhirne, 1983), there is not yet a global mapping of the actual spread of the aerosol that is adequate for modeling studies. Such an assembly of data should be a focus of effort over the next few years, especially since there was apparently continuing gas-to-particle conversion taking place over a period of several months.

Because interest exists in projecting future climatic effects even though data are lacking, estimates have had to be used to develop the pattern to be used in early model studies. Robock (1983) has estimated optical depth as a function of time from 1982 through 1984 based on theoretical model results of the spread of a dust cloud (Cadle *et al.*, 1976), but allowing additional time for gas-to-particle conversion. Although these projections may overestimate the spread of aerosol during the first few months (i.e., before the breakdown of the summer zonal circulation), this may be compensated for in part by underestimation of the spread once the aerosol becomes involved in the more active winter circulation. Comparison of Robock's estimates for January, 1983 with measurements of optical depth at 0.5 μm taken by the NASA Convair-990 indicate, for example, that Robock's values may overestimate optical depth slightly in the tropics and strongly in the sub-tropics (where measurements indicate greatly reduced optical depth), but underestimate optical depth in middle latitudes.

Despite these possible shortcomings, we have chosen to use Robock's estimates in order to provide a basis for intercomparison of his EBM results with our SDM results, and because, as indicated earlier, the temporal and spatial pattern of observations is not yet assembled.

3.4 *Time-Dependent Climatic Response to the El Chichón Aerosol*

Using Robock's assumed spread of the volcanic aerosol, an initial model simulation has been made covering the period April 1, 1982 to January 1, 1983. The initial temperature response is a cooling at latitudes below the volcanic cloud. Cooling also occurs near the sea-ice edge, a result due not to a radiative perturbation at that latitude, but to a small change in the date of melting induced by reduced poleward energy transport. At the end of the first six months, cooling of more than 0.2 K has occurred in the latitude band from the equator to 30°N, as shown in Fig. 5. Peak cooling during 1982 is indicated to occur where rainfall in desert regions is slightly increased, thereby allowing a slight albedo reduction and increased evaporative cooling of the surface. These local variations in the response are almost certainly latitudinally and seasonally dependent, indicating the necessity of using a model including such resolution. By late 1982, a nearly uniform cooling of about 0.2 K had occurred over the entire Northern Hemisphere, with only very slight cooling ($<$0.1 K) in the Southern Hemisphere. Although there was a slight polar amplification of the response, it was not as large as in our equilibrium simulation or as suggested by Robock's results. Temperature changes were larger over land and less over the oceans.

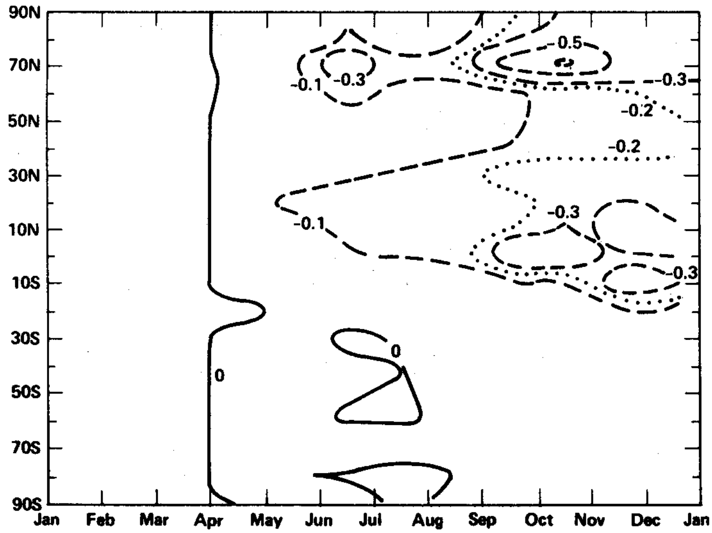

Fig. 5. Zonal average change in monthly average surface temperature (°C) assuming that the effect on stratospheric optical depth of El Chichón is represented by the pattern given by Robock (1983).

Just as for the equilibrium calculation, the hydrologic response occurred as the result of a slight southward shift in the ITCZ (see Fig. 6). The effect increased gradually after the eruption and was leading to changes in monthly average precipitation rate on the order of 10% at some latitudes by the end of 1982, with increased precipitation to the south and decreased precipitation in the drier, northern subtropical side of the ITCZ. Precipitation changes at other latitudes were quite small.

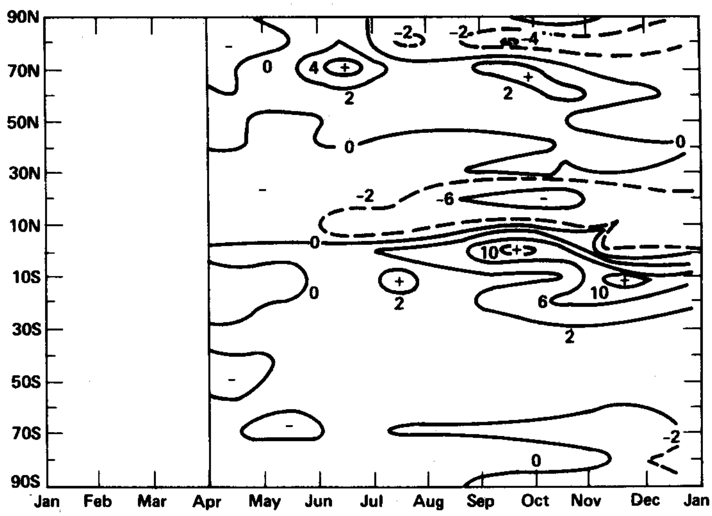

Fig. 6. Zonal average percentage change in precipitation rate assuming the stratospheric optical depth perturbation given by Robock (1983).

This shift in the ITCZ was accompanied by shifts in the zonal wind pattern (see Fig. 7). Of most interest was the apparent weakening of equatorial easterlies. Although this weakening is much smaller in magnitude than the observed weakening that contributed to the 1982 - 83 El Niño (Philander, 1983), it will be interesting to determine in later calculations with the LSDM whether coupling of the warming of equatorial sea surface temperatures (due to oceanic processes) and weakening of the easterlies (due to El Chichón's effect on the radiation balance) can be positively coupled in such a way to explain the unusual timing and magnitude of the recent El Niño.

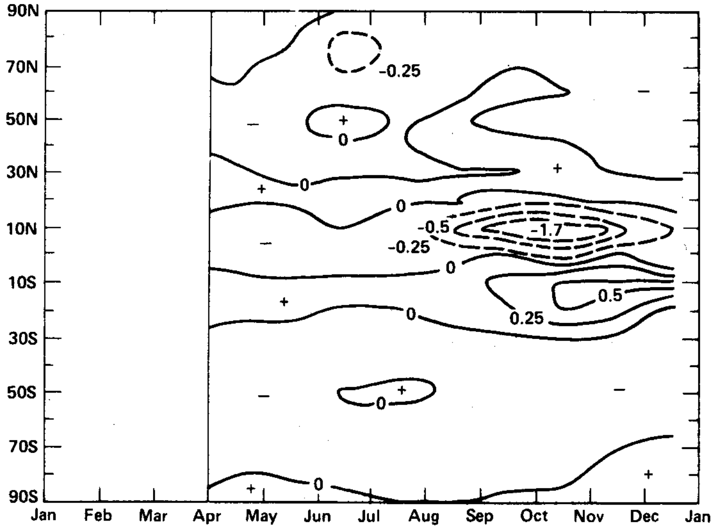

Fig. 7. Monthly average change in zonal average wind speed (m/s) assuming the stratospheric optical depth perturbation given by Robock (1983). A positive sign indicates stronger westerly or weaker easterly flow.

As expected in our model simulation with a slab ocean, ocean temperatures are changing more slowly and steadily than land temperatures. Nine months after the eruption, the global ocean temperature had decreased almost 0.1 K, the decrease being larger in the Northern Hemisphere and smaller in the Southern Hemisphere.

The trend in global average temperature is steadily downward the nine months after the eruption, and our results are in excellent quantitavive agreement with those of Robock (1982), who projects a global average cooling in 1982 of about 0.1 K. It will be important to investigate how long the cooling continues in a longer simulation with our model, since Robock (1983) projects ever larger cooling out to four years following the eruption (reaching a global average temperature decrease of about 0.4 K) and relatively slow recovery thereafter.

4. CONCLUSIONS

The El Chichón eruption has produced a Northern Hemisphere stratospheric aerosol cloud that is causing the largest radiative perturbation in the last 100 years, and which, although of opposite sign, is comparable, on a short-term basis during aerosol maximum loading, to the perturbation in radiative flux at the tropopause expected from doubling the atmospheric CO_2 concentration. As such, this event offers an unparalleled opportunity for investigating the characteristics of the climatic response to radiative perturbations, and for helping unravel the effects of volcanic eruptions on past climate.

There are, however, a number of complications, in addition to the sparsity of measurements of optical depth, aerosol characteristics, etc. Most important are the potential interactions that arise as the full climate system responds, assuredly only hinted at in the LSDM results. Not only can shifts in the latitudinal pattern of precipitation induce changes via evaporative cooling in temperatures that are larger or of opposite sign to those that would be anticipated from radiative perturbations alone, but shifts in the circulation pattern may also lead to other types of changes. While the interconnections remain speculative at this point, it is not inconceivable that the model-projected southward shift in the ITCZ could have contributed to the reduction of equatorial easterlies and thereby played a role in generation of the major El Niño that so drastically affected the 1982/83 weather in the Northern Hemisphere. Although such interactions cannot be completely investigated with a zonal model, nor in a model without much more representative ocean physics, simulations are planned in which the El Niño is imposed (both independent of and simultaneous with the El Chichón aerosol) so that more comprehensive model experiments can be suggested.

In summary, although the El Chichón eruption offers the potential for increasing understanding of climatic responsiveness, preliminary calculations indicate that the lessons to be learned will require extensive investigation and will not come easily.

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