Observed Perturbations of the Earth's Radiation Budget: A Response to the El Chichón Stratospheric Aerosol Layer?

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ABSTRACT

The Earth Radiation Budget experiment, launched aboard the Nimbus-7 polar-orbiting spacecraft in late 1978, has now taken over seven years of measurements. The dataset, which is global in coverage, consists of the individual components of the Earth's radiation budget, including longwave emission, net radiation, and both total and near-infrared albedos. Starting some six months after the 1982 eruption of the El Chichón volcano, substantial long-lived positive shortwave irradiance anomalies were observed by the experiment in both the northern and southern polar regions. Analysis of the morphology of this phenomena indicates that the cause is the global stratospheric aerosol layer which formed from the cloud of volcanic effluents. There was little change in the emitted longwave in the polar regions. At the north pole the largest anomaly was in the near-infrared, but at the south pole the near UV-visible anomaly was larger. Assuming an exponential decay, the time constant for the north polar, near-infrared anomaly was 1.2 years. At mid- and low latitudes the effect of the El Chichón aerosol layer could not be separated from the strong reflected shortwave and emitted longwave perturbations issuing from the El Niño/Southern Oscillation event of 1982-83.

1. Introduction

The introduction of a volcanically initiated aerosol layer into the terrestrial stratosphere has the potential of producing a measurable climatological response. The eruption of Mount Agung in Bali, for example, was noted to cause a decrease in the mean tropospheric temperature of up to 1°C (Newell, 1981). In 1815, the volcano Tambora in the Dutch East Indies erupted, dramatically—albeit temporarily—altering the global climate (Toon and Pollack, 1977), and producing the so-called "year without a summer."

Many factors combine to determine the extent of coupling between the Earth’s climate and a specific volcanic event. The e-folding time (that time required to yield an amplitude drop of 1/e) of stratospheric aerosol concentrations is relatively small (on the order of 1 year) compared to the oceanic time constant (from 3 to 4 years depending on the depth of the mixed layer). Because of this heat storage capacity, any climatological response is necessarily transient; the maximum terrestrial response cannot occur too quickly after the addition of a volcanic cloud due to the large oceanic thermal inertia. Indeed, the time evolution of the surface temperature, for example, is strongly dependent on latitude. The largest response and shortest time constant occur near the Arctic Circle, with a lesser response and longer time constant in the tropics (Chou et al., 1984). The latitude of the volcanic aerosol injection and the subsequent latitudinal distribution of the aged stratospheric cloud is a second consideration. The sulfur content of the magma (Krueger, 1983), the resultant global aerosol mass loading (McCormick and Swisler, 1983; Hoffman and Rosen, 1983a; McCormick et al., 1984) and the height of the eruption cloud (Rampino and Self, 1984) are also important considerations. Sections 3 and 4 address the formation and evolution of the stratospheric aerosol cloud produced by the El Chichón eruption.

The Earth Radiation Budget (ERB) experiment launched aboard the Nimbus-7 spacecraft in late 1978 is designed to measure, globally and regionally, various components of the Earth’s radiation budget. The timing of the El Chichón eruption, occurring nearly at the midpoint of the 6-year ERB dataset analyzed to date, provides an ideal opportunity to test the observability of any perturbations in the radiation budget components from an extraterrestrial platform. An overview of the ERB experiment is presented in section 2, while discussions of the observations themselves—the onset, variability and decay of the radiative response—occupy sections 5, 6 and 7, respectively.

2. Overview of the Earth Radiation Budget experiment

On 24 October 1978, the Nimbus-7 (N-7) spacecraft was launched into a sun-synchronous, near-polar orbit
with local-noon ascending and local-midnight descending nodes and a retrograde inclination to the equator of 99.3°. To minimize degradation in the optical trains of the various channels (caused by the interaction of deposited out-gassing containers and the solar UV), the experiment was not activated until 16 November 1978. At this time, full-time collection of ERB observations commenced, limited only by the constraint of available spacecraft power. The ERB was one of eight scientific instrument packages on the spacecraft. Their total power requirements were such that they could not all be operated simultaneously. As part of the compromise arrangement the ERB has normally operated on a 3 day on/1 day off duty cycle.

The ERB itself consists of three different sensor groups: a ten channel solar telescope array, four wide field-of-view (WFOV) fixed Earth-flux channels 11–14, and a biaxial narrow field-of-view (NFOV) scanning Earth radiance telescope array. The solar channel observations have received extensive analysis in the tenths-of-percent regime (e.g., Hickey and Alton, 1983) and are not relevant to this study. The NFOV sensors did not possess a lifetime of sufficient length to make possible the study of interannual variability. Further discussion will be limited to the WFOV earth-viewing sensors.

There are four WFOV channels. The total channel 12 is used to measure both reflected-solar and emitted-terrestrial radiation in a spectral band of 0.2 to 50 μm. At the same time, the shortwave channels 13 and 14 monitor reflected solar radiation in the spectral bands of 0.2–3.8 and 0.7–2.8 μm. Channel 11 is normally kept covered to reduce degradation and is used as a reference channel. Its spectral band is 0.2 to 50 μm. The calibrated output of these channels and their differences then yields total reflected shortwave, emitted longwave, near-infrared reflected, ultraviolet and visible reflected, and total exitant irradiances.

Reflected radiation in the 0.2–0.7 μm spectral regime is obtained by differencing the shortwave and near-infrared channels’ measurements; because there is little extraterrestrial solar energy in the spectral subregion of 2.8–3.8 μm, this contribution to the difference can be neglected. The extraction of the shortwave portion of the signal from the total incident flux is performed by the positioning of a pair of filter hemispheres composed of Suprasil-W fused silica over the appropriate detector. Although a single filter dome effectively blocks all longwave radiation longer than 3.8 μm, a second inner filter dome is employed to block the thermal emissions of the outer filter dome as it warms due to the absorption of the incident terrestrial longwave radiation. For the extraction of the near-infrared signal from the total incident flux, two similar filter domes are employed with a third red RG695 dome between them to block radiation between 0.2 and 0.7 μm (Jacobowitz et al., 1984).

Channels 12, 13 and 14 view the entire visible Earth disk at all times. Satellite-altitude (955 km) irradiance observations are taken at 4-second intervals throughout the 104-minute orbits. It should be emphasized at this time that this satellite-altitude dataset may not be simply reduced to the “top of the Earth’s atmosphere” (TOA) due to nonuniform weighting of radiances incident within the fields-of-view (FOVs) as noted in King and Curran (1980). Thus, the WFOV observations are actually integrals across the radius of the 29.6° earth central angle (ECA) visible earth disk; the half-power point radius is approximately 7° ECA (see Fig. 1).

Although calibrated to high precision in the laboratory at three times prior to the launch, with no evidence of any calibration drift (Hickey and Karoli, 1974), exposure to the in-flight orbital environment produced both trends and periodicities in the filtered channels’ (13 and 14) dataset, requiring the application of a set of calibration adjustments (Kyle et al., 1984; Ardanuy and Rea, 1984; Maschoff et al., 1984).

Qualitatively, the stability of the total-radiation channels 11 and 12 is remarkable. Quantitatively, measurements of total outgoing radiation as measured by the total channel 12 appear to be more than adequately accurate and stable. The sensitivity of this channel varies, after the first year in orbit, at a rate of one-tenth of a percent per year. This implies that the observed instantaneous net radiation (itself a function of the orbital plane of the satellite) and related products are sufficiently stable to render interannual climate observations possible (Ardanuy, 1983). Over three years of data had been taken prior to the 1982 eruptions of El Chichón.

3. Formation of the aerosol cloud

Between 28 March and 4 April 1982, the Mexican volcano El Chichón (17.3°N, 93.2°W) in Chiapas produced a series of major eruptions. Based on comparisons between the eruption cloud brightness temperatures and radiosonde ascents at Veracruz, as well as between satellite-imaged cloud motion vectors and the tropospheric and stratospheric motion fields, two, and perhaps three, of the volcanic plumes reached the stratosphere. Of these, the final eruption at 0522 LST 4 April was by far the largest. The massive cloud that formed clearly penetrated the tropical tropopause, moving well into the stratosphere (Matson and Robock, 1982). Several distinct ash and sulfur dioxide layers were subsequently observed: the highest one, resulting from the latter eruption, contained the bulk of the effluents.

Measurements of the stratospheric background H₂SO₄ vapor concentration in the altitude region of the El Chichón plume show that it is typically near saturation. The El Chichón cloud was rich in sulfurous gases, of which SO₂ was the predominant species. Pro-
production of sulfates and sulfuric acid followed the eruption from oxidation and other gas-phase chemical reactions. Thus, an immediate consequence of the injection of this eruption cloud into the stratosphere was the evolution of a high degree of H$_2$SO$_4$ supersaturation (Hofman and Rosen, 1983b), leading to spontaneous homogenous creation of minute H$_2$SO$_4$/H$_2$O droplets onto the volcanic and other condensation nuclei already present in the cloud. Though higher regions of the plume were inaccessible to direct aircraft interceptions due to their great height, active production of new sulfate aerosols was noted in the lower regions of the plume on 20–21 April 1982 (Mroz et al., 1983). Particle sizes were observed at this time to be generally less than 0.05 μm. This aerosol size distribution, resulting from the copious and simultaneous nucleation of many small particles, was only temporary due to the accretion of the background vapor onto the existing droplets. Hofman and Rosen (1983b) explain the appearance of an observed bimodal size distribution, with maxima at 0.02 and 0.7 μm, as a combination of the two types of growth mechanisms: new droplet nucleation on the one hand and a combination of collision, coalescence and growth of the preexisting distribution due to accretion on the other.

Balloon-borne particle counters indicated that the production of new droplets was still occurring through 18–19 May, but probably stopped in late June (Hofman and Rosen, 1983b), as evidenced by a rapid decrease in the concentration of the smaller mode. The larger 1 μm mode was noted to have no significant trend in concentration through late November. From terminal velocity estimates for a 1 μm droplet at 25 km, a continued growth of these particles due to accretion is required (Hofman and Rosen, 1983b), presumably from H$_2$SO$_4$ vapor scavenged from the smaller droplets.

4. Evolution of the aerosol cloud

Tropospheric components of the eruption cloud were found to disappear within six days (Matson, 1982). The stratospheric portion, after some modifications due to local wind shears, propagated rapidly westward, forming a well-defined zonal band in approximately three weeks (Krueger, 1983; Matson, 1982). The onset of the cloud over the Mauna Loa observatory at 19.5°N, as observed by Lidar, occurred on 9 April 1982 (DeLuisti et al., 1983). The cloud was noted over Nagoya, Japan (35°N, 137°E) as measured by increases in backscattered light as early as 22 April; on 4 May
the onset of the dense region of the aerosol cloud occurred (Iwasaka et al., 1983).

In late October and early November 1982, seven months after the eruptions, aircraft measurements of the latitudinal distribution of aerosol optical depth were taken between 46°N and 46°S (McCormick and Swisслer, 1983; Swisслer et al., 1983; Spinhirne, 1983). The results showed that the bulk of the global stratospheric aerosol burden was confined to the tropics between latitudes 5°S and 35°N. Using a solar photometer, Spinhirne measured the stratospheric aerosol optical thickness at 6 wavelengths between 0.44 and 0.87 μm. At 0.87 μm he found an optical depth of 0.04 at 35.5°N latitude versus 0.02 at 35.5°S latitude. However, at 0.44 μm the optical depth was 0.06 at this latitude in both the north and the south. At 0.44 μm a peak optical depth of 0.16 was found at 19°N latitude. Previously Clemesha and Simonich (1983) reported lidar aerosol backscatter signals from the stratosphere at 0.59 μm which were much above normal on 9 July 1982, at São José dos Campos, Brazil (23°S, 46°W). The integrated backscatter between 17 and 27 km increased even more in the August to October period.

The Stratospheric Aerosol Monitor (SAM II) experiment on the Nimbus-7 satellite monitors polar stratospheric aerosol optical depths at the 1 μm wavelength. It is a sun photometer and thus can make measurements only when it views the sun at satellite sunrise and sunset. In the Nimbus-7 orbit the measurements vary seasonally between 64° and 80° north and south latitudes. According to McCormick and Swisслer (1986) the corresponding background aerosol optical depth was under 0.004 in the Arctic at the time of the eruption. By June it had increased to 0.01 and reached a maximum greater than 0.1 by March 1983; it then declined slowly, reaching a value just under 0.04 by October 1983. In the Antarctic the optical depth was 0.003 in early April 1982 and declined slowly until June, when it started to increase rapidly and peaked at about 0.009 in August. In late September it suddenly dropped to 0.002, but at the end of October the optical depth increased rapidly again reaching a maximum of about 0.025 by the end of November. It retained this value until April 1983 when a slow decline set in. Again, a sharp drop occurred in September to a value of 0.004 followed by recovery to just under 0.02 by the end of December.

Between 9 and 20 May 1983, aircraft measurements of the latitudinal distribution of the aerosol optical thickness were taken between 72°N and 56°S (McCormick et al., 1984; Spinhirne and King, 1986). The results showed that the aerosol cloud was no longer confined to the tropics. Peak optical depths which had been noted at the latitude of El Chichón six months earlier were now found near 50°N, with substantial concentrations noted out to the northern limit of the study near the Arctic Circle. Similarly, in the Southern Hemisphere the aerosol cloud thickness had decreased equatorward of 40°S but had increased near 50°S. In this flight, Spinhirne measured the optical depth at 10 wavelengths between 0.44 and 2.23 μm. Again the north had many large aerosol particles with radii near 1.0 μm, with few found in the south.

Thus, by the end of November 1982, large amounts of El Chichón–derived stratospheric aerosols had reached both the northern and southern polar regions. However, the aerosol particles were, in general, much smaller in the south than in the north. Thus the SAM II 1 μm optical depth of 0.025 over the Antarctic might underestimate the visible and UV optical depths by 60 to 150%. In the Arctic, the SAM II measurements should more closely represent the average optical depth. Unfortunately, there is little overlap between the SAM II polar measurement regions and the latitudes covered by Spinhirne's solar photometer measurements. Thus some extrapolation is required. This is particularly true in the south.

5. Onset of the observed Earth radiation budget response

The first conspicuous observations of perturbations in the Earth's radiation budget in response to the El Chichón stratospheric aerosol layer occurred approximately 7 months after the sequence of volcanic eruptions (28 March to 4 April 1982). Beginning in late October 1982, and becoming increasingly evident through November and December, a positive bias shift in the satellite-altitude irradiances occurred between 60° and 90° latitude in both Arctic and Antarctic. The effect occurred simultaneously in all three of the broadband ERB channels corresponding to shortwave, near-infrared and total-radiation spectral bands. The most dramatic signal, and the first noticed, occurred in the near-infrared channel over the north-polar cap.

Figure 2 illustrates six years of near-infrared irradiances taken over this north polar cap, the Arctic, on the ascending node in the months of November and December. Immediately evident is the secular seasonal variation in light level due to the solar declination approaching and departing its winter solstice limit. The data taken during the first 4 years of ERB operation show striking similarities; indeed, when binned into half-monthly averages, the corresponding standard deviations are less than 1/2 W m⁻². The near-infrared irradiances taken in year-5 (1982) presented in this figure depart strikingly from this pattern, as the amount of reflected solar radiation increased due to the higher stratospheric albedo. Statistical significance is assured, with the post-eruption observational anomalies exceeding 4–8 standard deviations that of the pre-eruption data. The anomaly response approaches 5 W m⁻² (Table 1) during this time period, indicating an increase in planetary albedo at this latitude of approximately...
Fig. 2. Onset of the near-infrared polar radiative response. Note the consistency of the four “background” years prior to the eruptions, the strong signal in the year following the eruptions, and the decayed signal one year later.

20%. The relative radiometric responses of the shortwave channel and the total channel (which includes the entire shortwave spectral band within its response domain) are on the order of 1½ to 2 times larger than that of the near-infrared channels; however, because of the increased amount of solar energy available, the estimated enhancements to the planetary albedo correspond closely within all three channels.

The year-6 (1983) irradiances in Fig. 2 indicate the decay in the El Chichón aerosol layer by the fall of 1983. This will be discussed further in section 7. Without any question, the strength, time duration and temporal coherence of this perturbation in the extant reflected-radiation field, and hence the planetary albedo and net radiation (for the polar latitudes), is unparalleled in the 6+ year data record compiled by the ERB experiment on board this polar-orbiting spacecraft. Based on analyses of long-term instrument stability, including both that of the shortwave and near-infrared channel’s offsets at night and the sensitivities of all the channels determined via “pitch-maneuver” monitoring (Jacobowitz et al., 1984) of the reference solar disk, the observed radiative perturbation cannot possibly be accounted for by calibration errors. Furthermore, not only is solar activity of too low an amplitude to account for this perturbation [the standard deviation of the solar variability about the mean solar constant is approximately 0.07% (Hickey and Alton, 1983)], but the period in question does not contain any unusual solar behavior. In addition, the effects of the El Chichón volcanic cloud on solar insolation received at Fairbanks, Alaska (64.8°N, 147.9°W) closely paralleled those reported here, both in terms of the time of the onset (early to mid-November, 1982) (Wendler, 1984) and also in magnitude. Taken as a whole, all evidence points to the conclusion that perturbations in the Earth’s radiation budget parameters are the cause of the observational anomalies detected by the ERB experiment.

Our efforts to detect the El Chichón signal at mid- and tropical latitudes have been baffled by several factors. The two most important are

- the orbit of the Nimbus-7 satellite, which crosses the Earth’s equator at local noon and the terminators in the polar regions;
- the massive regional perturbations in the Earth’s radiation budget parameters in the tropics and mid-latitudes caused by the El Niño/Southern Oscillation. These perturbations started in the summer of 1982 and peaked in the 1982–83 winter (Ardanuy and Kyle, 1986);
### Table 1. Bi-weekly summary of six years of near-infrared irradiances (W m⁻²) and irradiance anomalies (see text for description).

<table>
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<th>Year</th>
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<td>29.6</td>
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<tr>
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<td>38.1</td>
<td>31.6</td>
<td>28.1</td>
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**Irradiance anomalies (W m⁻²)**

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**Irradiance enhancement (%)**

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**Mean decay rate (% yr⁻¹)**

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**Time constant (years)**

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<tr>
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<td>1.0</td>
<td>1.4</td>
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* The ERB experiment was activated on 16 November 1978.

** Taken between the corresponding months for the years 1982/1983 and 1983/1984.

† Due to increasing aerosol optical thickness at the time, no physically reasonable time constant can be obtained.

In the Nimbus-7 ERB data, unambiguous signal enhancements associated with the El Chichón stratospheric aerosol layer occur only near satellite sunrise and sunset. Due to the satellite orbit these always occur in the polar regions. Near the terminators the seant factor associated with the large solar zenith angles cause the effective aerosol optical depth to be many times the zenith optical depth and thus strongly enhance the signal. The Earth Radiation Budget Satellite (ERBS) was launched in October 1984 into an orbit inclined 56° to the Earth’s equator, (Barkstrom, 1984). In a little over a month’s time it crosses the terminator at all latitudes between 56°S and 56°N latitude. If it had been in orbit prior to the El Chichón eruptions, we could undoubtedly have observed the aerosol cloud at all latitudes, except perhaps in the tropics during the peak (January–May 1983) of the El Niño perturbations in the zonal averages.

It is unfortunate that the El Chichón eruption, and the resultant climatological response, is imbedded in the time period of the most pronounced El Niño episodes of the past century (Rasmussen and Wallace, 1983). As such, one may not infer that all major terrestrial climatic changes following the El Chichón event are due to the presence of the resultant aerosol cloud (Quiroz, 1983). In fact, perhaps only through modeling studies will the two respective responses ever be truly uncoupled. However, based on the phenomenological characteristics of tropical and polar radiation budget perturbations to be reported on in the following section, a limited partitioning of the two responses is possible.

### 6. Intra-annual variability of the observed response

Figures 3a, b illustrate monthly averaged, time-latitude cross sections of irradiance fields taken at the satellite altitude for the period January 1982–October
suggesting that the aerosol particles are relatively small. In the northern summer of 1983 the near-infrared spectral region appears to contribute 60% or more of the total anomalous reflected signal. This corresponds to the findings of Spinhirne and King (1986), who found the Southern Hemisphere stratospheric aerosol particles to have much smaller mean radii than those in the Northern Hemisphere. The theoretical calculations of King et al. (1984) corroborate the effect that the different particle size distributions would have.

The data is studied on a global scale in Figs. 4a–d for the fifth data year (November 1982 to October 1983), when the ERB signal from the stratospheric aerosol clouds was the strongest. In order to enhance the signal, daily radiation anomalies (instead of the monthly averages used in Fig. 3) from the shortwave reflected channel 13 (0.2–3.8 μm) and the total radiation channel 12 (0.2–5.0 μm) are presented for both the ascending-node and descending-node orbit halves. Thus Fig. 4b corresponds roughly to Fig. 3b, though at a higher temporal resolution. The surface plots for the total channel irradiances can also be interpreted as instantaneous net radiation anomalies, if solar variability is neglected. Because of the satellite’s altitude and orbit, it is within the earth’s shadow for only ½ of its orbit. While in the earth’s shadow, channel 12 measures simply the longwave exitant flux. The regions between 40°S and 40°N latitude on the DN half of the orbit are almost always observed during the satellite’s night.

a. Shortwave radiative perturbations

The perturbations in the reflected shortwave radiation are shown in Figs. 4a and b. The December–February polar perturbations are marked with the letter “A” in Fig. 4a and the letter “C” in Fig. 4b. The corresponding perturbations in May–July 1983 are marked by “B” and “D” respectively. Note that these anomalies amount to between 15% and 30% of the total signal in these regions near the terminator. The corresponding anomalies in channel 12 (0.2–50 μm) are designated by ("G", "L", "K", and "H"). Channel 12 measures the sum of the solar-reflected and Earth-emitted radiation. Comparison of the channel 13 and 12 anomalies indicates that they consist chiefly of an increase in the reflected solar radiation with little change in the Earth-emitted infrared. The equality of the northern and southern signals (regions “A” and “C”) in channel 13 in the December–February period is a little surprising. Reference to Fig. 3b, however, indicates that after the daily values are averaged, the southern signal is some 75% of its northern counterpart. The SAM II data, and also that of Spinhirne and King (1986), confirm that a somewhat stronger northern signal would have been expected. In channel 12 the south polar signal “H” in June and July 1983 is not well
developed. In analyzing Figs. 3 and 4, the results from channel 13 should be given slightly less weight than those from channels 12 and 14. Although the channel 13 calibration is reasonably well understood (Kyle et al., 1984, 1985), it is known to be slightly less stable than channels 12 and 14.

The behavior of these polar anomalies appear related to the El Chichón stratospheric clouds for three reasons: 1) similar analyses taken in the years prior to the volcanic eruption do not contain this type of pattern; 2) our results fit (in time) solar observations of El Chichón aerosols by the SAM II experiment and other experiments; 3) the response contours follow lines of constant sun angle. This is a fundamental property of such a stratospheric aerosol, whose diffuse reflection (albedo) for a constant aerosol optical thickness and wavelength
is strongly an increasing function of solar zenith angle. The computations of King et al. (1984), for example, show that the albedo near the Arctic Circle is double that expected at 45°N due to the introduction of a stratospheric aerosol cloud with uniform optical depth, in both shortwave and near-infrared spectral regimes. Further, they show that the bimodal particle size distribution, first noted by Hofman and Rosen (1983b), plays a major role in enhancing the radiative response in the near-infrared in the Arctic.

Harshvardhan (1979) modeled the perturbation of the zonal radiation balance by a stratospheric aerosol layer composed of 75% H₂SO₄. His results predicted the strong functional dependence of absorbed solar energy on solar zenith angle and showed that the resultant radiative perturbations induced by an aerosol layer would be strongest at high latitudes. For an optical depth of 0.1, reductions in absorbed (and enhancements in reflected) solar energy were predicted to reach 4–9 W m⁻² near the poles. The results of this study
correspond closely to the simulations, as shown in Figs. 4a–d. Harshvardhan also estimated that a mean anomaly of 3.5–4.5 W m\(^{-2}\) should occur in the tropics and mid-latitudes. However the observed signal should be less than this at local noon and larger near sunrise and sunset. The Nimbus-7 is in a sun-synchronous orbit and observes all regions between 55°S and 55°N within one hour of local noon on the ascending node. We therefore expect the El Chichón aerosol clouds to produce anomalies of less than 2% and normally about 1% in the reflected radiation signal (channel 13).

Examination of Fig. 4a shows zonally-averaged reflected radiation anomalies of 20–30 W m\(^{-2}\) in the tropics and mid-latitudes. These amount to from 9–15% of the total reflected radiation and are much larger than would be expected from the El Chichón aerosol cloud. Further, the high anomalies at one latitude border low anomalies at nearby latitudes. Recall that, during satellite night, channel 12 measures the outgoing longwave radiation. Thus Fig. 4d between 40°N and 40°S is an analysis of longwave radiation. Comparison of Figs. 4a, c and d indicates that, in the nonpolar regions, negative anomalies in the reflected radiation ("E" in Fig. 4a) tend to be associated with positive anomalies in the outgoing longwave radiation "I" in Fig. 4d and vice versa. This type of pattern is normally associated with large-scale temporal and latitudinal shifts (I and J in Fig. 4d) in the normal tropical tropospheric cloud patterns. Neither in magnitude nor structure is it the effect expected from the El Chichón stratospheric aerosol layer. It is however the typical signature of the strong El Niño/Southern Oscillation (ENSO) event which went through its strongest phase for the year starting in June 1982. The Nimbus-7 ERB TOA outgoing longwave fluxes have been analyzed by Ardanuy and Kyle (1986). The longwave anomalies peaked in January 1983 with regional values as high as −88 W m\(^{-2}\) and +65 W m\(^{-2}\) at the TOA, or −67 W m\(^{-2}\) and +49 W m\(^{-2}\) at satellite altitude. However, the zonal anomalies peaked later in April and May 1983 with satellite altitude peak anomalies of +12 and −8 W m\(^{-2}\).

Thus, during the year (November 1982–October 1983) interannual perturbations in the Nimbus-7 observed Earth radiation parameters in the polar regions can be chiefly attributed to the El Chichón stratospheric aerosol layer. However, the large perturbations in the tropics and mid-latitudes were principally due to the ENSO event.

b. Longwave radiative anomalies

It is difficult to isolate effects which might presumably be due to the ENSO event from those possibly caused by the El Chichón eruption series of 29 March–4 April 1982. The enhanced stratospheric aerosol amounts are believed to reduce the terrestrial OLR field (Chou et al., 1984; Harshvardhan, 1979). For an aerosol optical depth increase of 0.1, the OLR could be expected to decrease by 0.5 W m\(^{-2}\) at the poles and 1–1.5 W m\(^{-2}\) in the tropics. This could account for negative anomalies, but not positive.

Figure 5a, b illustrates the behavior of two parameters that are descriptive of the large-scale behavior of the zonally-averaged OLR during the period under discussion. They are anomalies in the two spherical-harmonic amplitudes that describe the global-mean OLR (Fig. 5a) and the equator-to-pole gradient (Fig. 5b). The derivation of these figures is discussed in detail by Ardanuy and Kyle (1986).

Note that the behavior of the global mean can be characterized by three modes: below normal prior to December 1982, near normal between December 1982 and May 1983, and again below normal after May 1983. It is difficult even to attempt to decouple the radiative effects deriving directly from the stratospheric aerosol cloud from those caused by the ENSO event. The 1–1.5 W m\(^{-2}\) decrease in the global mean during the first 6 months of the figure, spanning the period between shortly after the eruption and the time when the aerosol cloud was released from the tropics into the high latitudes, is consistent with theory. Here the strongest negative perturbations would occur when the greatest aerosol cloud optical depths (0.1) were over the tropics where they are until December 1982.

Typically, the equator-to-pole gradient has a magnitude of from −26 (solstice) to −30 (equinox) W m\(^{-2}\). Thus, a positive anomaly (Fig. 5b) indicates that the

![GLOBAL MEAN](image)

![EQUATOR–TO–POLE GRADIENT](image)

**FIG. 5.** Anomalies in the monthly-averaged, global-mean outgoing longwave radiation (a) and equator-to-pole gradient (b) in W m\(^{-2}\).
tropics are anomalously cool relative to the poles. Between December 1982 and January 1983 the parameter makes a transition from +0.4 W m⁻² to -1.4 W m⁻². It is conceivable that this is caused by the relatively sudden release of the aerosol cloud from the tropics to the midlatitudes. Equally likely, and no doubt contributing to the time series, is the evolution of the ENSO phenomenon at the same time (Ardanuy and Kyle, 1986).

7. Decay in amplitude of the observed response

Table 1 presents a summary of six years of northern winter near-infrared observations taken in the ascending-nodal half of the Nimbus-7 orbit. These zonal averages, which are averaged across the latitude range of 60 to 90°N, show marked stability (both on the part of the earth and the instrument) for the first four data years. However, beginning in October of the fifth data year, a radiative response attributable to the El Chichón stratospheric aerosol cloud is evident. This is most obvious in the set of irradiance anomalies, which is simply taken as the departure from the time-average of the first four years. During this year (shown here in half-months from October 1982 through February 1983), mean radiative excesses over this polar cap in the near-infrared regime approach 5 W m⁻², an enhancement of almost 20% above the typical value. The largest radiative responses are noted here in late December and early January. This is due in part to the strong dependence of the diffuse reflection by the stratospheric cloud on the solar zenith angle. Also an important factor here is the time dependence of the aerosol optical thickness, itself a function of the stratospheric aerosol mass loading.

Given a set of measurements of the enhancement in the atmospheric reflectance due to the presence of the El Chichón cloud soon after the eruption, as well as one year later, it is possible (assuming an exponential decay) to estimate the time constant for the atmospheric radiative response. Based on the estimates from December through February, a little under one-half the initial radiative response (e.g., January, 1983) is noted one year later (January 1984).

Assuming that the functional distribution of the aerosol column density is exponential, this yields an estimate for a time constant of approximately 1.2 years, or 14 months. This figure is in agreement with the Northern Hemisphere stratospheric mass loading observations taken during a set of survey flights, notably January–February 1983 and January 1984 (McCormick et al., 1984). It appears that the mass loading in this Northern Hemisphere region continues to increase through October and November 1983, and only peaks in the latter half of December. This can be inferred from the half-monthly time constant estimates, which increase to 2.7 years in late November, 3.8 years in early November, and 7.3 years in late October. Prior to mid-October 1983, there was a notably smaller atmospheric response than present a year later, indicating that much of the aerosol cloud had not yet penetrated into the region at that time.

In the Southern Hemisphere polar regions, there is relatively little aerosol loading compared to the Arctic. Furthermore, as discussed in section 4, there is less of a concentration in the 1 μm particle-size mode. As a consequence the mean anomaly peaks of the near-infrared irradiiances are correspondingly lower, averaging only 1–1.7 W m⁻² in December 1982 (Fig. 3a) and in June 1983 for the AN observations (not shown). These perturbations completely vanish by June 1984 during the sixth year of data. Thus, a time constant on the order of 1 year is evident for the Southern Hemisphere as well, though this Southern Hemisphere signal (as evident from the SAM II dataset) is less coherent than in the north.

8. Conclusions

Over five years of near-infrared, shortwave and total radiation WFOV measurements taken by the N-7 ERB experiment were used to examine perturbations in the Earth's radiation budget. Clearly evident near each of the poles (between 60° and 90°) are phenomena which appear to be responses to the El Chichón stratospheric aerosol layer. The responses are first evident in October 1982 as enhancements in the satellite-altitude irradiances in each of the three measured spectral bands.

The aerosol-induced perturbations in the reflected solar radiation are strongly dependent on solar zenith angle with the largest increases in reflection occurring near the terminator. The latitudinal bands exhibiting this brightening are about 30 deg in width, centered more or less over the terminator, with the El Chichón responses dominating for solar zenith angles greater than 75 deg. The latitudinal location of these bands varies with season, showing up on the ascending-nodal ("day") side of the orbit for the winter hemisphere and on the descending-nodal ("night") side for the summer hemisphere.

The aerosol-induced perturbation to the Earth's radiation budget, as recorded by the ERB experiment on board the Nimbus-7 spacecraft, clearly is limited for the most part to polar latitudes. As expected, the stratospheric aerosol cloud acts to increase the total planetary (surface, tropospheric, and stratospheric) albedo. This increase is shown to be regionally as much as 20%, resulting in an increase of on the order of 8–10 W m⁻² in excessive solar shortwave reflection at satellite altitude. This perturbation is shown to propagate directly into the shortwave component of the net radiation, suggesting that the polar regions in the year(s) following the El Chichón eruption act as an enhanced cold source. There were also strong zonal perturbations in the tropics of the order of +10–15% (20–30 W m⁻²) in the shortwave and +6–7% (10–12 W m⁻²) in the
outgoing longwave radiation. These, however, are of an entirely different nature, with neighboring increases and decreases in the albedo, and with the longwave decreasing when the shortwave increases and vice versa. This pattern indicates large scale temporal and latitudinal drifts in the normal tropical cloud fields. The tropical perturbations must therefore be assigned principally to the intense El Niño episode which occurred at about the same time as the El Chichón stratospheric aerosol layer. Although regional and zonal perturbations were large, average global values were little affected.

Our analysis of the Nimbus-7 ERB failed to identify perturbations in the tropical albedo that could be associated with the El Chichón aerosol layer. This should not be interpreted as a statement that such a radiative response did not exist but that the El Niño perturbations, combined with the satellite local-noon equator crossing time, made it impossible to isolate the relatively small expected signal.

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