Geof. Int. Vol. 23-3, 1984, pp. 351 - 362

SPECTRALLY RESOLVED MEASUREMENTS OF THE EL CHICHON CLOUD, MAY 1982 - AUGUST 1983

G. W. LOCKWOOD*
N. M. WHITE*
D. T. THOMPSON*
H. TÜG* ** ***

RESUMEN

Se hicieron diariamente mediciones de la extinción atmosférica de 330 a 840 mn en mayo de 1982 y mensualmente después, las cuales revelaron el arribo y evolución de la nube de desechos volcánicos y condensados sobre Flagstaff, Arizona. La profundidad óptica de la nube alcanzó su pico ≈0.3 el 15 de mayo y permaneció a niveles de alrededor de 0.1 hasta fines de 1982. En el otoño de 1983 había caído a ≈0.05. La dependencia de la extinción de la longitud de onda es congruente con el transporte global de la nube y con los cambios en la distribución de tamaños de las partículas reportados en otros trabajos de este volumen.

ABSTRACT

Measurements of the atmospheric extinction from 330 to 840 nm were made daily in May 1982 and monthly thereafter, revealing the arrival and evolution of the cloud of volcanic debris and condensates over Flagstaff, Arizona. The optical depth of the cloud peaked at ≈0.3 on 15 May and remained at levels of about 0.1 throughout the remainder of 1982. By the fall of 1983, it had dropped to ≈0.05. The wavelength dependence of extinction is consistent with the global transport of the cloud and with the changes in its particle size distribution reported in other papers in this volume.

* *Lowell Observatory (H. Tüg as a Guest Investigator)*
** *Ruhr-Universität Bochum*
*** *Alfred Wegener Institut, Bremerhaven*

Astronomers routinely measure the vertical atmospheric transmission in order to reduce spectrophotometric measurements of celestial objects to "above the atmosphere" values. The resulting "extinction coefficients" (= −2.5 log transmission) are expressed in stellar magnitudes per air mass.

Unfortunately, however, the archival preservation of long-term extinction records at various observatories is more uncommon than one might think, since extinction coefficients are often considered ephemera. Furthermore, since they are acquired and reduced by a variety of methods on an individual basis by different astronomers, they are often not mutually consistent.

Unusually extensive extinction records, based upon broadband ($\Delta\lambda \approx 100$ nm) measurements, in the blue and yellow have been collected at the Lowell Observatory since about 1953, owing to an emphasis upon very long-term photometric programs (e.g., Jerzykiewicz and Serkowski, 1966). Intermediate-band ($\Delta\lambda \approx 10$ nm) 470- and 550-nm data have been obtained regularly several times per month since 1972 at the 0.5-meter reflector. These measurements are of uniformly high quality and are thus suitable for a study of long-term trends now being carried out by Lockwood and Thompson, as well as providing background "pre-volcanic" extinction levels for this paper.

In addition, low-resolution spectral data covering the wavelength range 330 - 840 nm have been obtained since 1980. A chance juxtaposition of events resulted in the acquisition of exceptionally numerous and accurate daily and nightly measurements during much of May 1982, just as the El Chichón volcanic cloud arrived over Flagstaff. These observations were an essential part of an experiment to intercompare the monochromatic fluxes of the Sun and the star Vega using a novel technique invented by Tüg (1982).

We first noticed the cloud on 8 May during daytime observations, but we did not immediately recognize its volcanic origin. When we contacted the Kitt Peak National Observatory (located 325 km south of Flagstaff), we learned that the cloud was apparently even thicker there. Later, confirming reports of high extinction came from the McDonald Observatory (Texas) and the Mauna Kea Observatory (Hawaii). The rapidly increasing optical thickness compromised our principal experiment but yielded a detailed extinction record as a by-product, described briefly by Livingston and Lockwood (1983).

Our May observations were made with a scanning Cassegrain spectrometer attached to the 0.6 - meter Morgan telescope of the Lowell Observatory (elevation 2.2 km). Afterwards, we used the same scanner on the 1.8 - meter Perkins reflector to obtain additional extinction data about once a month.

Using the "Bouguer method," the atmospheric absorption is determined as a function of the zenith distance of a rising or setting celestial object. The computed slope of the relationship between apparent brightness and air mass for each program wavelength gives the extinction coefficient k(λ) in units of stellar magnitude/ air mass.

A single measurement, requiring about 10 minutes of observing time, consists of discrete intensity measurements every 5 nm over three wavelength ranges dictated by order separation requirements in the spectrometer: 330 - 540, 500 - 710, and 700 - 840 nm. The separate regions were combined after reduction to give the wavelength dependence of the extinction coefficient, an example of which is illustrated in Figure 1.

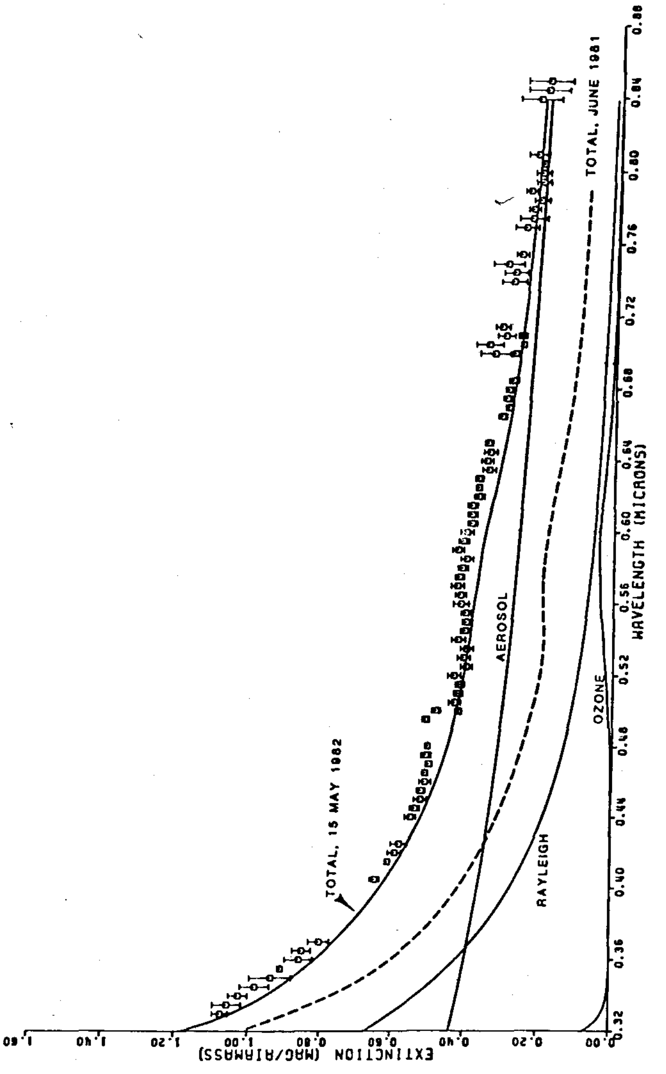

Fig. 1. Wavelength dependence of extinction for 15 May 1982 with component parts displayed. The total extinction in units of stellar magnitude per air mass or (−2.5 log transmission) is the upper solid line fitted to the observations. The total is the sum of the components indicated (aerosol scattering, Rayleigh scattering, and ozone absorption). The total extinction for June 1981 is shown as a dashed line. (From Livingston and Lockwood, 1983).

Typically, for the Sun we recorded five to ten scans each morning over an air mass range from ≈1.0 to ≈3.0. Each complete observation consisted of two sweeps in each spectral region. Four to six scans per region were made in the middle of the night as Vega rose in the east. After May 1982, the nighttime data are more sparse, typically three to five scans per spectral region.

Figure 1 shows the total extinction recorded during the day on 15 May 1982, when the visual extinction at 550 nm was 0.40 mag/air mass, corresponding to 69% transmission. The highest value occurring in May, and by far the largest ever recorded in Flagstaff, 0.47 mag/air mass, was obtained just a few hours earlier during the previous night. Even higher extinction was seen at Kitt Peak around this time (Livingston and Lockwood, 1983), leading to the conclusion that, at least during May, the cloud thinned out northward over Arizona.

Normally in May the visual extinction attains its annual maximum of ≈0.18 ± 0.02 mag/air mass (85% transmission): thus, the transmission of the volcanic cloud alone recorded in Flagstaff was as low as ≈77%. To illustrate the wavelength dependence of the total extinction which is typical for this time of year, a curve based on four nights of observation in June 1981 is shown as a dashed line on Figure 1.

In Figure 1, the total extinction $k(\lambda)$ is resolved into additive components due to Rayleigh scattering, aerosol scattering, and the ozone absorption bands ($\lambda<350$ nm and 450 nm $< \lambda <$ 700 nm), i.e.,

$$k(\lambda) = A_{aer} + A_{ozone} + A_{Rayleigh} ,$$

(cf. Tüg, White, and Lockwood, 1977) and the extinction model of Hayes and Latham, 1975). A_{aer} in this case includes the normal background tropospheric aerosol *plus* the volcanic aerosol. In the adopted model, $A_{Rayleigh}$ and A_{ozone} are known, and the data are fit for the residual aerosol extinction $A_{aer} = A_0\lambda^{\alpha}$, where λ is expressed in micrometers.

The tropospheric aerosol component changes on daily and seasonal time scales; and, while the average seasonal variation is fairly predictable, the daily variation is random. In Table 1 we summarize the data available from Kitt Peak and from Lowell for estimating the baseline average total extinction and the aerosol extinction alone, prior to the eruption of El Chichón. Values are given for five representative wavelengths between 350 and 710 nm.

The observed mean values for Kitt Peak as published by Hayes (1982) are listed in the first line. The second line gives the predicted extinction due just to Rayleigh scattering and ozone absorption, computed for the 2.1-km elevation of Kitt Peak. Finally, the estimated seasonally averaged aerosol values are tabulated in the third line. This aerosol can be fit with the coefficients $A_0 = 0.02$, $\alpha = -0.9$.

The total extinction at 550 nm is known to undergo an annual variation at Kitt Peak reaching a minimum of ≈ 0.13 mag/air mass in winter and a maximum of ≈ 0.18 mag/air mass in late spring. Hayes' mean data thus appear to be slightly weighted toward the lower wintertime values.

A similar computation in Table 1 for the Lowell Observatory is based upon just four nights of observation in June 1981, one year prior to the eruption of El Chichón. The residual aerosol is estimated after subtraction of the Rayleigh and ozone components, and fitting it gives $A_0 = 0.05$, $\alpha = -0.7$. Adding the fitted aerosol back to the Rayleigh and ozone values (bottom line of Table 1) gives the total extinction for June 1981. These values are consistent with those found at Kitt Peak, allowing for the seasonal variation; and the adopted exponent, $\alpha = -0.7$, is acceptably close to the value −0.87 determined at the same site in May 1976 by Tüg, White, and Lockwood (1977).

Table 1

Baseline extinction coefficients

Wavelength (nm)	350	410	470	550	710
Kitt Peak (elevation 2.1 km)					
Observed mean	0.60	0.32	0.22	0.15	0.07
Predicted Rayleigh + Ozone	0.55	0.26	0.17	0.11	0.04
Residual aerosol	0.05	0.06	0.05	0.04	0.03
($A = 0.02, \alpha = -0.9$)					
Flagstaff (elevation 2.2 km)					
Observed Lowell, June 1981	0.65	0.36	0.29	0.18	0.11
Predicted Rayleigh + Ozone	0.54	0.26	0.17	0.11	0.04
Residual aerosol	0.11	0.10	0.12	0.07	0.07
($A = 0.05, \alpha = -0.7$)					
Fitted aerosol	0.12	0.10	0.09	0.08	0.07
Fitted total	0.66	0.36	0.26	0.19	0.11

In Table 2 we list the observed volcanic aerosol extinction coefficients for five representative wavelengths extracted from the total set of 80 wavelength points between 330 and 840 nm. At each tabulated wavelength we have computed a normal point consisting of the mean of values at three to five adjacent wavelength points spaced at 5-nm intervals; hence in this part of the analysis we used only about one-fourth of the total data available. Then we subtracted the estimated

Table 2

Observed volcanic aerosol extinction

MST Date		=	350	410	470	550	710	Total		Volcanic		r^2
								A	α	A	α	
1982	May	7.1	0.06	0.05	0.07	0.03	--	0.03	−2.2	0.02	−1.2	0.39
		8.1	0.14	0.10	0.10	0.06	--	0.04	−2.1	0.02	−1.7	0.90
		8.3	0.10	0.11	0.09	0.09	--	0.04	−2.2	0.07	−0.3	0.45
		10.0	0.12	0.12	0.12	0.15	0.12	0.13	−0.7	0.13	+0.1	0.07
		13.1	0.15	0.16	0.19	0.19	0.10	0.13	−1.0	0.11	−0.5	0.25
		13.6	0.06	0.13	0.14	0.16	0.11	0.17	−0.4	0.19	+0.7	0.25
		14.0	0.17	0.22	0.26	0.26	0.24	0.19	−0.9	0.32	+0.5	0.48
		14.4	0.25	0.22	0.26	0.28	0.12	0.19	−0.8	0.12	−0.8	0.44
		15.0	0.23	0.24	0.25	0.27	0.27	0.32	−0.1	0.30	+0.3	0.89
		15.3	0.28	0.25	0.25	0.21	0.22	0.16	−0.1	0.18	−0.4	0.75
		16.3	0.17	0.13	0.14	0.18	0.12	0.17	−0.6	0.12	−0.3	0.17
		17.0	0.20	0.17	0.17	0.18	0.14	0.15	−0.7	0.13	−0.4	0.72
		17.3	0.14	0.12	0.13	0.13	0.10	0.14	−0.7	0.09	−0.4	0.63
		19.0	0.22	0.19	0.18	0.24	0.20	0.27	−0.1	0.21	0.0	0.00
		19.3	0.14	0.15	0.16	0.13	0.13	0.16	−0.6	0.12	−0.2	0.29
		19.6	0.06	0.10	0.11	0.08	0.06	0.10	−0.8	0.07	−0.2	0.04
		20.0	0.08	0.11	0.11	0.09	0.05	0.07	−1.2	0.05	−0.8	0.41
		20.3	0.04	0.04	0.04	0.05	--	0.05	−1.3	0.06	+0.5	0.61
		20.6	0.09	0.07	0.09	0.07	0.03	0.06	−1.4	0.02	−1.4	0.70
		21.0	0.12	0.09	0.05	0.07	0.06	0.05	−1.5	0.04	−0.9	0.50
		21.3	0.04	0.03	0.03	0.03	0.01	0.06	−1.2	0.01	−1.7	0.77
		22.9	0.01	0.03	0.02	--	--	0.07	−0.8	--	--	--
1982	Jun	3	0.18	0.16	0.15	0.16	--	0.18	−0.4	0.13	−0.3	0.50
		4	0.15	0.13	0.11	0.13	--	0.16	−0.3	0.09	−0.4	0.36
		11	0.07	0.07	0.07	0.10	--	0.13	−0.4	0.14	+0.7	0.61
	Jul	6	0.04	0.05	0.07	0.07	0.06	0.13	−0.2	0.09	+0.6	0.46
	Sep	29	0.09	0.10	0.11	0.13	0.11	0.15	0.0	0.14	+0.3	0.47
		30	0.10	0.12	0.14	0.13	0.13	0.17	−0.1	0.16	+0.3	0.47
	Nov	26	0.13	0.12	--	0.19	0.15	0.19	−0.3	0.19	+0.4	0.36
	Dec	19	0.04	0.07	0.09	0.13	0.10	0.15	+0.1	0.21	+1.3	0.65
1983	Jan	22	0.10	0.09	0.15	0.11	0.10	0.13	−0.3	0.11	+0.1	0.01
	Feb	24	0.04	0.02	0.02	0.08	--	0.05	−1.1	0.11	+1.4	0.17
	Apr	18	0.25	0.29	0.20	0.26	0.06	0.22	−0.5	0.25	0.0	0.00
		19	--	--	0.10	0.02	0.03	0.16	+0.6	--	–	--
		20	--	0.01	0.05	0.09	0.09	0.16	0.0	0.46	+3.6	0.67
		26	0.14	0.13	0.08	0.08	0.12	0.12	−0.5	0.08	−0.4	0.13
		28	0.01	0.02	0.06	0.08	0.10	0.16	+0.2	0.45	+3.3	0.85
	May	21	0.02	--	0.06	0.01	--	0.06	−0.3	--	–	--
		22	0.05	0.06	0.10	0.09	0.12	0.18	−0.1	0.20	+1.2	0.84
		30	0.49	0.27	0.13	0.11	0.11	0.10	−1.2	0.04	−2.1	0.77
	Jun	29	--	0.08	0.07	0.10	0.09	0.20	+0.3	0.11	+0.4	0.32

normal (i.e., non-volcanic) extinction given in Table 1, leaving what we presume to be a best estimate of just the residual volcanic aerosol. We used the Lowell 1981 mean (fitted total) values as the baseline for all of the dates in Table 2, except September 1982 to February 1983, where we used the seasonally averaged "winter"

Kitt Peak values. We suspect that the adopted baseline estimate may be too high by about 0.02 at 550 nm during this interval; therefore, the September-February volcanic extinction may be slightly underestimated. The transmission of the volcanic cloud for any date and wavelength in Table 2 is $T = 10^{-0.4\,k}$, where k is the tabulated value. The optical depth $\tau = k/1.0857$.

The data for May 1982 were obtained during both the day and the night, as indicated by the fractional civil (MST) date in the table. Subsequent data are night-time values only, and the listed date is the date of midnight MST.

We fitted the observed values of the aerosol extinction in two ways. First, as is our custom in the course of routine data reduction, after subtracting the Rayleigh and ozone components, we simply fitted $A_{aer} = A_0 \lambda^{\alpha}$ for the residual (tropospheric + volcanic) aerosol extinction, using the measured values at each of the ≈ 80 individual wavelength points. The resulting values of A_0 and α are given in Table 2. The computed aerosol exponent α derived in this way is shown as a function of the total extinction at 550 nm on Figure 2. Two continuous day-night sequences are indicated by a connecting dotted line in order to illustrate the rapid change in the total cloud opacity which occurred during May 1982.

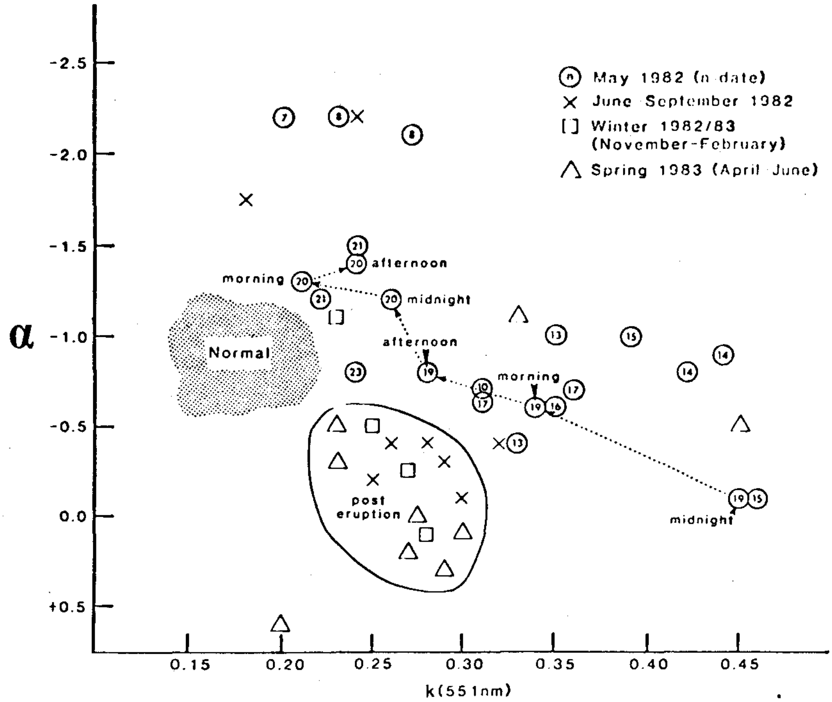

Fig. 2. The wavelength exponent α of the total aerosol extinction (cf. Figures 3b, 4b) as a function of the total extinction observed at 550 nm (tropospheric + volcanic). Consecutive day-night data points for May 1982 are connected by a dotted line.

Subsequently, α (tropospheric + volcanic) has stabilized for the time being at a value near 0, compared with a normal value of −0.7 to −0.9. By the winter of 1982, the total extinction at 550 nm decreased to a value about 0.1 mag/air mass higher than normal, corresponding to a transparency at the zenith of about 80%, compared with a normal value near 90%.

In order to study the cloud extinction alone, we then fitted the estimated *residual volcanic aerosol* values in Table 2 with an aerosol function of the same form, leading to the values of A_v and α_v, and the square of the correlation coefficient r^2 given in the last three columns of the table.

All the random errors of observation and any systematic error associated with the assumed tropospheric aerosol are included in the volcanic cloud data as a fractionally large component. This accounts for the many low values of r^2, where a significance level of 80% ($r^2 > 0.47$) is attained only for about half the nights. Nonetheless, we believe that the gross time behavior of the cloud extinction is preserved, as indeed is suggested in Figure 2, where the data points are distinctly clustered by date.

Figure 3 shows several observed and computed extinction parameters corresponding to the individual daily and nightly observations in May 1982. The rise and fall of extinction associated with a thick transient cloud were fairly symmetric, centered on 15 May. The top panel of Figure 3 shows the observed volcanic extinction at 550 nm (i.e., the total observed extinction minus the adopted mean of 0.19 from Table 1). The remaining panels give α (total), α_v (volcanic), A_0 (total), and A_v (volcanic).

During mid-May, the volcanic aerosol can be characterized by $\alpha_v \approx 0$, during which time the cloud optical thickness varied from ≈ 0.1 to ≈ 0.3 (third and fifth panels of Figure 3). Before and just after this brief interval, when the cloud optical thickness was <0.1, $\alpha_v \approx -2$, indicative of a distinctly different particle size distribution. Corresponding values of α and A for the total extinction (normal + volcanic), as shown in the second and fourth panels of Figure 3 are similarly perturbed.

An elementary interpretation of the wavelength dependence of the scattering from the volcanic aerosol in May, as seen in Flagstaff, is consistent with the stratospheric aerosol concentrations measured *in situ* over southern Texas by Hofmann and Rosen (1983a, b). An upper cloud at ≈ 25 km consisting of large droplets was confined to latitudes 0° to 30°N, while a lower cloud of small droplets was more widespread in latitude.

The lower cloud may have been present over Flagstaff during all of May, because we observed $\alpha_v \approx -2$ around 8 May and again around 21 May (Figure 3). However, during the week centered on 15 May, when the volcanic extinction was highest, we

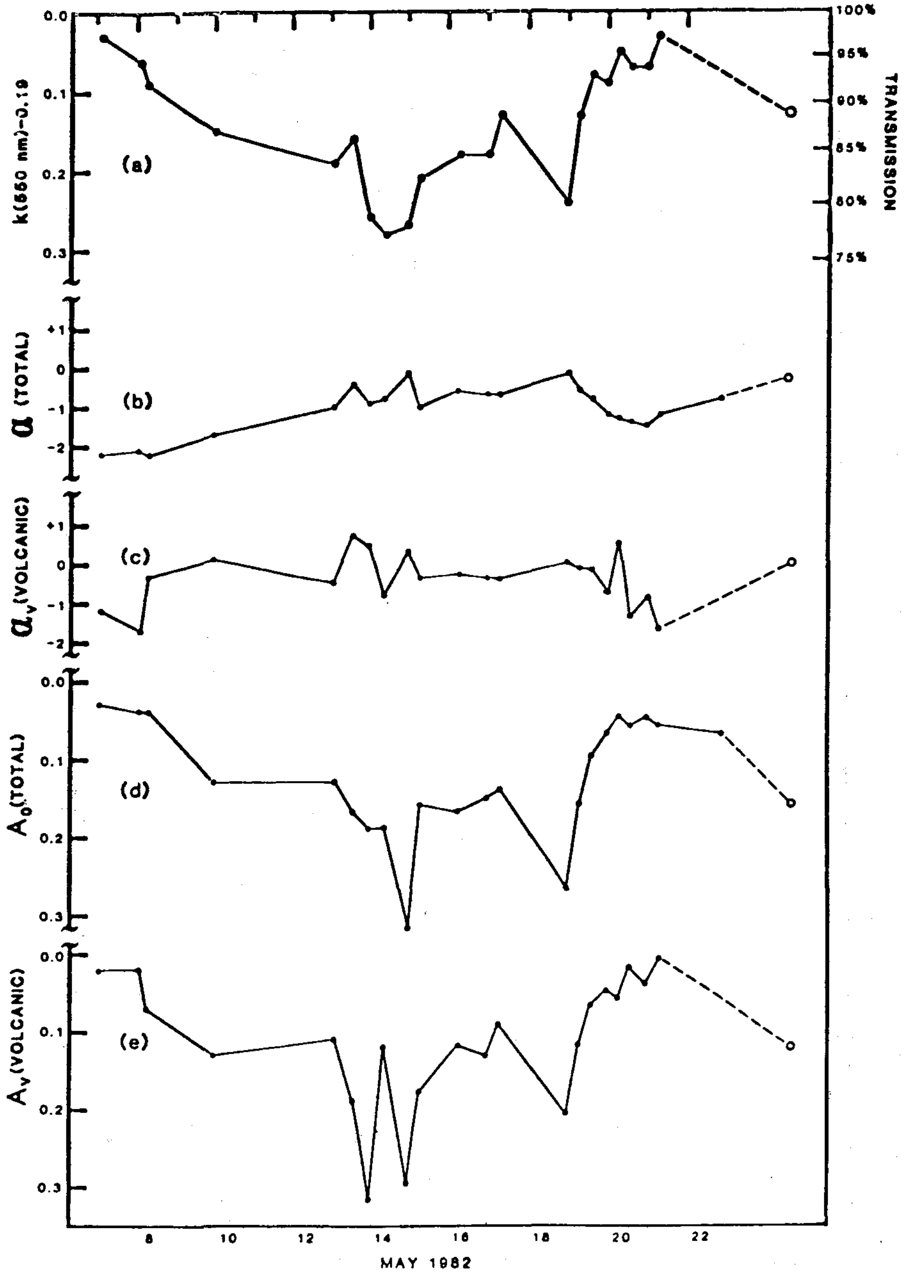

Fig. 3. (a) Volcanic extinction at 550 nm (observed minus the normal May value of 0.19 stellar magnitudes per air mass) during May 1982. The transmission of the cloud is indicated by the right-hand scale. (b) and (d) Fitting the total observed aerosol (tropospheric + volcanic) with the function $A_0\lambda^{\alpha}$, given the indicated values of A_0 and α. All 80 wavelengths were used for this calculation. (c) and (e) A_v and α_v for the volcanic cloud alone, using the data from the five wavelengths in Table 2.

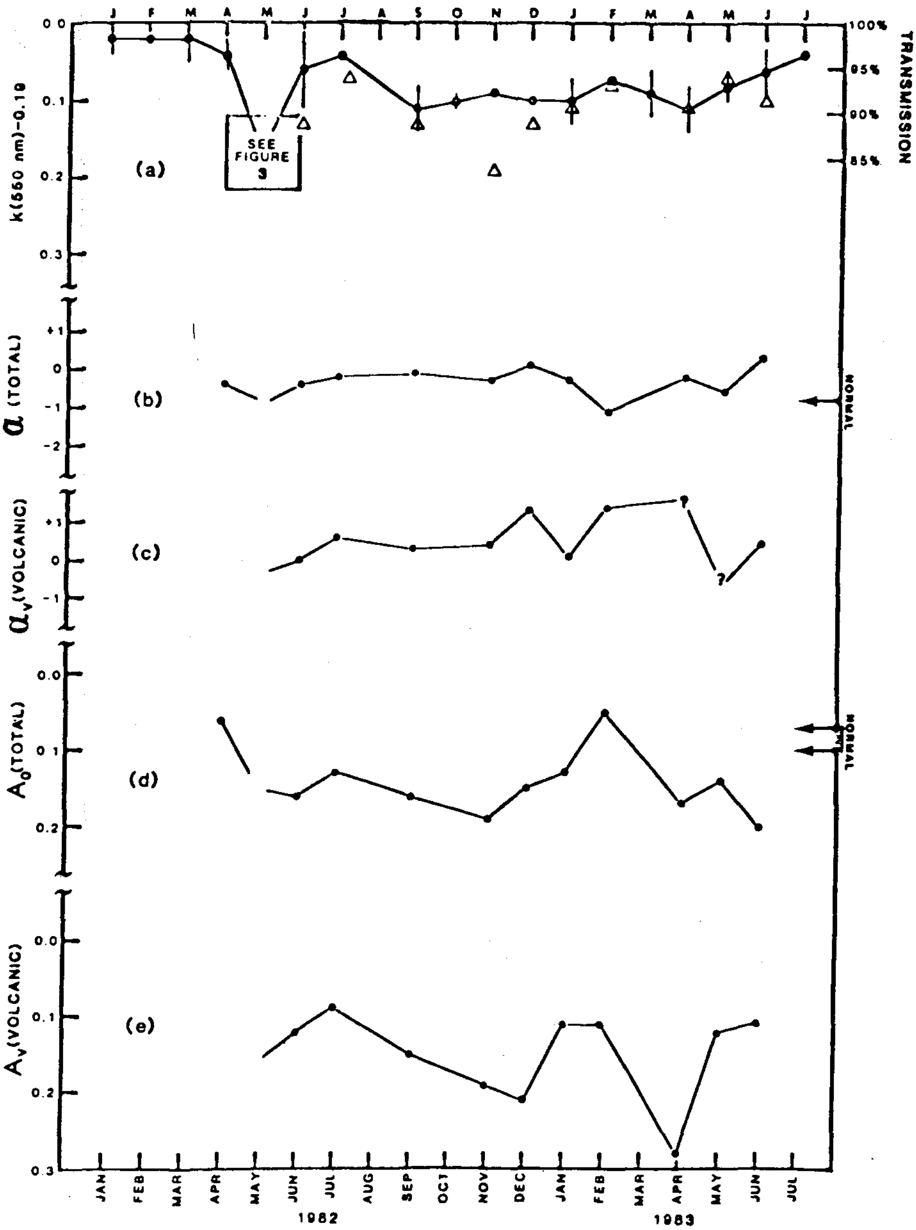

Fig. 4. (a) (Solid line) Monthly mean values of the volcanic extinction at 550 nm from the independent unpublished photometry. The 90% confidence interval is indicated as an error bar for those months in which at least four observations were obtained. Scanner points from Table 2 are shown as separate unconnected symbols. (b, c, d, e) Same as Figure 2.

observed $\alpha_v \approx 0$, suggesting that the northern latitude limit of the upper cloud of large, neutrally scattering particles had temporarily reached Flagstaff (latitude 35°). This hypothesis is consistent with the report, mentioned above, of even higher extinction during May at Kitt Peak (latitude 32°). From the top panel of Figure 3, we estimate crudely that the maximum optical depth of the upper cloud was ≈ 0.2 and that of the lower cloud was ≈ 0.1.

The subsequent evolution of the volcanic cloud through the spring of 1983 is shown on Figure 4, which incorporates observations from Table 2. These data are relatively sparse and of lower quality than the highly accurate values for May 1982. We have therefore augmented the spectral data with monochromatic extinction coefficients at 550 nm obtained typically four to eight times per month by Thompson and Lockwood in the course of an independent photometric program. These measurements, minus appropriate prevolcanic monthly mean values taken from unpublished data 1972-1981, are presented as monthly mean "volcanic" extinction coefficients in the top panel of Figure 4. Error bars refer to the 90% confidence interval for all months in which at least four observations were obtained. In this panel, the scanner data are shown by separate, unconnected symbols. The remaining panels illustrate the scanner data in Table 2.

We note a slight excess optical depth, $\Delta\tau \approx 0.02$ in January - March 1982 relative to the long-term (1972 - 1981) mean, perhaps attributable to the "mystery cloud," which preceded the El Chichón eruption. In April (six nights), the extinction increased steadily, from $\Delta\tau \approx 0.03$ on April 2, to ≈ 0.06 on April 26, perhaps heralding the initial incursion of the El Chichón cloud, seen also at Kitt Peak by late April. However, such small fluctuations are common in springtime, and we took no notice of them.

Following the presumed departure of the upper El Chichón cloud from the sky over Flagstaff in late May 1982, the total extinction returned nearly to prevolcanic levels. The excess (volcanic) optical depth was only ≈0.06 in late June (nine nights) and ≈ 0.04 in mid-July (three nights). However, by September it rose again to about 0.10, where it remained throughout the fall and winter of 1982. Around May 1983, thirteen months after the eruption, the excess extinction at 550 nm began to decline very slowly, to ≈ 0.06 in June (six nights) and again in September-October (three nights).

The wavelength dependence of the volcanic aerosol scattering also evolved slowly during this period, as shown in the third panel of Figure 4. The exponent α_v increased from ≈ +0.5 in the fall of 1982 to +1 or more in early 1983 (with an exceptional value of −2, probably spurious, seen on 30 May 1983). Sampling of the cloud by aircraft (Russell *et al.*, 1983) and balloon (Hofmann and Rosen, 1983b) confirmed the continuing nucleation of large ($r \approx 1\,\mu m$) particles and droplets, which is qualitatively consistent with our data.

To summarize briefly, after May 1982 the excess extinction at Flagstaff was essentially constant for a full year. Now, a year and a half after the eruption, the excess has declined by nearly half. Therefore, a two -or three- year time scale for the ultimate clearing of the volcanic cloud seems reasonable.

ACKNOWLEDGEMENTS

This research has been carried out, in part, through grants from the Deutsche Forschungsgemeinschaft, the National Science Foundation, and the National Aeronautics and Space Administration. GWL thanks the University of Texas and McDonald Observatory for their hospitality during fall 1983.

BIBLIOGRAPHY

HAYES, D. S., 1982. *Kitt Peak National Observatory Newsletter* No. 21, p. 5.
HAYES, D. S., and D. W. LATHAM, 1975. *Astrophys., 197,* 593.
HOFMANN, D. J., and J. M. ROSEN, 1983a. *Geophys. Res. Lett. 10,* 313.
————————, 1983b. Abstract published for IUGG Symposium R - 2, 19/20 August 1983, Hamburg, Federal Republic of Germany.
JERZYKIEWICŻ, M., and K. SERKOWSKI, 1966. *Lowell Obs. Bull.* No. 137.
LIVINGSTON, W., and G. W. LOCKWOOD, 1983. *Science 220,* 300.
RUSSELL, P. B., V. R. OBERBECK, J. F. VEDDER, G. V. FERRY, E. P. CONDON, E. P., K. G. SNETSINGER, D. M. HAYES, W. O. FONG, K. D. TABOR and M. A. KRITZ, 1983. Abstract published for IUGG Symposium R-2, 19/20 August 1983, Hamburg, Federal Republic of Germany.
TÜG, H., 1982. *Astron. Astrophys. 105,* 395.
TÜG, H., N. M. WHITE and G. W. LOCKWOOD, 1977. *Astron. Astrophys. 61,* 679.

(Accepted: April 3, 1984)