Volcanic Effects on Turbidity and Irradiances and Their Dependence on Surface Wind Direction

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ABSTRACT

Solar irradiances, atmospheric turbidity and meteorological variables measured at the University of Michigan are analyzed to determine effects of the 30 m wind direction on irradiance and turbidity changes caused by the El Chichón volcanic cloud. Results for the period with the largest volcanic effects, from 26 October 1982 through mid-June 1983, are compared with results for the same eight-month period in 1979–80, 1980–81, 1981–82 and 1983–84.

Effects of boundary-layer turbidity for winds from southerly directions occasionally masked effects of the stratospheric volcanic cloud on solar irradiances and sunphotometer estimates of Ångström turbidity parameters. As a result, volcanic effects could be quantified most reliably for winds only from northerly directions. The largest changes occurred with 30 m winds from the north-northwest octant, for which the volcanic cloud caused the average 500 nm aerosol optical depth to increase from 0.15 to 0.28, the turbidity coefficient to increase from 0.08 to 0.17, and the wavelength exponent to decrease from near unity to 0.6. The ratio of diffuse-to-direct solar irradiance increased from 0.10 to 0.21.

For winds from southerly directions, average turbidity was larger and more variable, and irradiance and turbidity changes due to the volcanic cloud were smaller. The smallest changes occurred with 30 m winds from the east-southeast octant, for which the cloud caused the optical depth to increase from 0.29 to 0.31, the turbidity coefficient to increase from 0.09 to 0.16, and the wavelength exponent to decrease from 1.3 to 0.9. The ratio of diffuse-to-direct irradiance increased from 0.15 to 0.22.

Daily totals of solar irradiances for 22 cloudless days from 26 October 1982 to 8 June 1983 showed the following average percentage changes from average conditions caused by the cloud: direct normal, −24; diffuse, +87; global, −5; global spectral (630–2800 nm), −1; and south-facing 42.3°-inclined, −5.

1. Introduction

A source of uncertainty in studies of volcanic effects on surface-based measurements of solar irradiances and atmospheric turbidity is in separating the percentage of observed changes caused by a stratospheric volcanic cloud from that caused by tropospheric aerosols. Measured irradiances and turbidity parameters estimated from photometric measurements of direct normal solar irradiance are affected in complex ways by the concentrations, particle size distributions, and constituents of both the volcanic cloud and tropospheric aerosols (Deirmendjian, 1973). Changes in water vapor and aerosol concentrations in the atmosphere's first several hundred meters alone have been shown to cause large changes in extinction coefficients (Tomasi, 1982). Work by Peterson et al. (1981) for North Carolina and by Uboegbulam and Davies (1983) for eastern Canada showed that boundary-layer turbidity at these locations depends heavily on the trajectory of the air in relation to both local and distant aerosol sources.

In the present paper, a method in which the air trajectory is implied is used to determine and account for the range of differences between effects caused by a volcanic cloud and those caused by tropospheric aerosols. The method consists of sorting irradiance and turbidity data according to wind direction measured at 30 m and comparing results obtained with and without the El Chichón volcanic cloud.

The cloud arrived over the University of Michigan irradiance and meteorological measurement facility (42°17′N, 83°44′W, 270 MSL) between 24 and 26 October 1982. Its arrival had been anticipated since the time El Chichón erupted in southern Mexico (17.33°N, 93.20°W) between 28 March and 4 April 1982 (Smithsonian Institution, 1982). After remaining at latitudes south of 30°N until early fall, the stratospheric cloud, composed largely of sulfurous compounds at altitudes between 24 and 31 km (Matson, 1984), began a rapid movement northward, reaching latitudes of 40°N and higher in November and December 1982 (Rao and Bradley, 1983; Wendler, 1984).

Both 24 and 26 October were cloudless days at the measurement facility and had similar temperature, wind, humidity and surface visibility conditions. Clear-sky values of turbidity parameters and solar irradiances representative of average values were measured on the 24th, but they changed markedly on the 26th. Departures from average values on the 26th included a 100% increase in aerosol optical depth, a 30% decrease in direct normal irradiance, an 88% increase in diffuse irradiance, and a 7% decrease in global irradiance. The conclusion that these departures were due to the volcanic cloud was based on a comparison with values of these variables measured at the facility in October of prior years with no known volcanic effects, a cloudless sky, similar solar zenith angles, comparable precipitable water, and an influx of a clean polar air mass.

In this paper, data obtained before and after the eight-month period from 26 October 1982 to mid-June 1983, when the strongest effects of the volcanic cloud were measured, are analyzed. Results obtained with 409 coincident measurements of solar irradiances and turbidity parameters during this period are compared with results obtained with 566 measurements for the same period in 1979–80, 1980–81, 1981–82 and 1983–84. As discussed below, the 1983–84 period is considered to be representative of conditions without volcanic effects. Data obtained during the 1.5-day passage of the Mount St. Helens volcanic cloud on 21–22 May 1980 are shown for comparison but are not included in the 409 samples that are representative of background conditions.

2. Irradiance, turbidity and meteorological measurements

Automatic recordings of six irradiance variables and six atmospheric variables as one-minute averages have been made at the University of Michigan since August 1979 (Ryznar, 1981). Irradiance measurements include global (horizontal and inclined), direct normal, diffuse, global with RG2 filter (630–2800 nm), ultraviolet (280–390 nm) and atmospheric (4500–50 000 nm). Simultaneous meteorological measurements include temperature, dewpoint, station pressure and 30 m wind speed and direction. In addition, periodic measurements with a 3-wavelength Volz sunphotometer (Volz, 1974) were made during cloudless conditions for calculations of aerosol optical depth, Ångström turbidity coefficient and wavelength exponent (Ångström, 1929, 1930, 1961), and precipitable water. From August 1979 to 1984, over 1700 such measurements were made, each of which was matched in time with the corresponding one-minute average of irradiance and meteorological variables.

The sunphotometer measurements were processed in terms of turbidity parameters with the following expression for aerosol optical depth developed by Ångström (1929, 1930) with coefficients that characterize the solar radiation scattering and absorption properties of an aerosol:

$$\tau_a(\lambda) = \beta\lambda^{-\alpha}, \qquad (1)$$

where $\tau_a(\lambda)$ is the aerosol optical depth due to scattering and absorption, β the Ångström turbidity coefficient, and α a so-called size distribution parameter.

The exponent α represents a theoretical simplification of the fact that scattering of solar radiation has a certain complicated relationship to wavelength (Paltridge and Platt, 1976). It is an indicator of the aerosol particle size distribution in the optically effective size range from about 0.1 to 1.0 μm. Increasing values of α imply a steepening size distribution function with a relative increase in the number of small particles. A value of 1.3 for α was found by Ångström to be a representative average, but α can vary from near zero for a size distribution dominated by particles a few microns in diameter, such as those in volcanic clouds or in smoke from forest fires, to near 4 for a distribution with a predominance of molecular sizes.

The Ångström turbidity coefficient β is proportional to the number density, or concentration, of scattering particles. In a study of mean annual turbidity in the United States, Flowers et al. (1969) found that τ_a (converted from base 10 to base e) at 500 nm varied from about 0.12 in relatively unpolluted air to about 0.3 in polluted air. If a value of 1.3 is accepted for α, these values of τ_{500} give $\beta = 0.05$ and 0.32, respectively. It can be noted that for a wavelength of 1 μm, β and τ_a in (3) are equivalent. Cho (1980) found a linear relationship between β and τ_{500}.

Values of τ_a were calculated with values for $\tau_R(\lambda)$ and $\tau_{O_3}(\lambda)$ and with methods provided in instructions accompanying the sunphotometer (Volz, personal communication, 1978). τ_a was calculated for wavelengths of 500 and 880 nm with the equation:

$$\tau_a = (\ln V_0 - \ln V - \ln F)M^{-1} - \tau_R - \tau_{O_3}, \qquad (2)$$

where V is the meter reading of the photometer corresponding to the intensity of direct normal irradiance, V_0 the calibration meter reading corresponding to direct normal irradiance at the outer limit of the earth's atmosphere and obtained by extrapolation to zero airmass with a Langley plot (Shaw, 1983), F the correction factor for Earth–Sun distance, the M the absolute optical airmass calculated with the method of Kasten (1964) and corrected for station pressure. Values of τ_R (500 nm, p_0) = 0.140, τ_0 (500 nm) = 0.0092, and τ_R (880 nm, p_0) = 0.0151 based on the work by Hoyt (1977) were used in the computations of τ_a. More recent work by Young (1981) indicates that the values of τ_R may be about 2% too small.

With values of τ_{500} and τ_{880}, the exponent α was calculated with the equation:

$$\alpha = -\left(\frac{\ln\tau_{500} - \ln\tau_{880}}{\ln 0.5 - \ln 0.88}\right). \qquad (3)$$

Values of precipitable water were calculated with the 880 and 940 nm sunphotometer measurements (Volz, 1974). They were compared with values obtained from the National Weather Service Radiosonde Station at Flint, Michigan, 60 km north of the measurement facility and found to agree within about 6%.

3. Wind direction effects

Figures 1a and 1b show monthly averages of τ_{500} (Fig. 1a) and diffuse/direct irradiance ratio (Fig. 1b) from February 1980 through June 1984 for wind directions in the quadrant 45° either side of north. The numbers are sample sizes and the vertical lines are standard deviations. Data for some months are missing due to excessive cloudiness, a lack of winds from a north quadrant, or both.

With consideration given to small sample sizes for some months, the variables in both figures show similar trends and other characteristics. Both have summertime maxima and wintertime minima, for example. The larger summertime values were caused mainly by larger aerosol concentrations and precipitable water amounts. There were only 16 values of precipitable water less than 1 cm from June through September and only 41 values greater than 1 cm from November through March. The large values and standard devia-

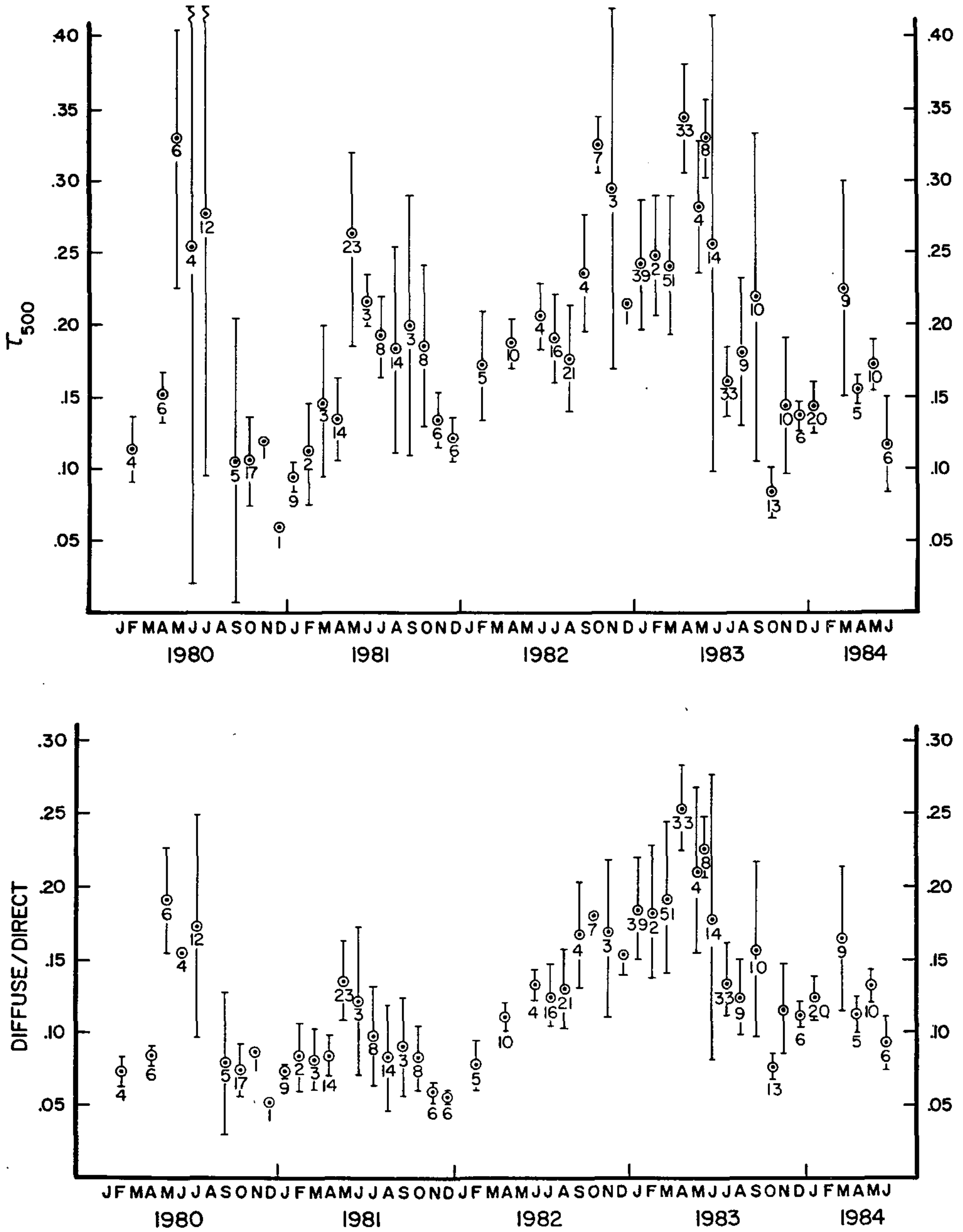

FIG. 1 (a). Monthly averages of 500 nm optical depth for wind directions between 315° and 045° from February 1980 through June 1984. The numbers are sample sizes and the vertical lines are standard deviations. (b). As in (a) except that the ordinate is the ratio of diffuse to direct solar irradiance.

tions in late May 1980 are due to effects of the Mount St Helens volcanic cloud that passed over the facility on 20–21 May (Ryznar et al., 1981) and are not included in the analysis described below. The large value for March 1984 resulted from measurements made on one day after clouds dissipated but precipitable water remained large.

The arrival of the main stratospheric cloud from El Chichón is evident by marked increases in both variables in October 1982, and its diminution is evident by a gradual return to values representative of average summer conditions in June 1983. In both figures the value with 8 samples is from 1–15 June 1983 and the much smaller value with 14 samples is for 16–30 June. A similar return to average conditions in mid-1983 was reported by Carroll (1984) and Wendler (1984). An unknown percentage of the variability in the data obtained during the eight-month period with the strongest effects is due to changes in the characteristics of the cloud itself.

The results of categorizing turbidity and diffuse and direct irradiances according to on-site measurements of wind direction are shown in Figs. 2a and 2b. Average values of τ_{500} in Fig. 2a and the diffuse/direct irradiance ratio in Fig. 2b are shown with and without the volcanic cloud for each 45° octant of wind direction. Values obtained with and without the volcanic cloud are shown by the outer and inner arcs, respectively, for each octant. The numbers in the middle of each arc are standard deviations for each average. Of major importance to an interpretation of these results is that both variables are categorized only according to wind direction measured at a height of 30 m. As with the results in Figs. 1a and 1b, they contain, therefore, important effects of a range of solar zenith angles between about 30° and 70° and a range of precipitable water between about 0.1 and 4 cm.

Preliminary results reported by Baker et al. (1984) with data obtained from October 1982 through January 1983 showed linear relationships between τ_{500} and the diffuse/direct irradiance ratio for various zenith angles and precipitable water with and without the volcanic cloud that are applicable to interpreting the results shown in Figs. 2a and 2b. The following are examples of these results:

(i) The largest average percentage increases in τ_{500} and the diffuse/direct ratio caused by the volcanic cloud were 87% (from 0.15 to 0.28) and 103% (from 0.10 to 0.21), respectively, and occurred with winds from the north-northwest (NNW) octant. The smallest increases were 8% (from 0.29 to 0.31) for τ_{500} and 48% (from 0.15 to 0.22) for the diffuse/direct ratio and occurred with winds from the east-southeast (ESE) octant. The average increases for all wind directions were 47% for τ_{500} and 79% for the diffuse/direct ratio.

(ii) The smallest values of τ_{500} and the diffuse/direct ratio and the least variability occurred with winds from northerly directions.

(iii) The largest values and most variability occurred with winds from southerly directions.

Statistical tests of differences between means were carried out with the means and standard deviations given in Figs. 2a and 2b to determine if the differences between mean values obtained with and without the cloud were statistically acceptable. A two-tail test, with a risk of rejection of 0.05 (Duncan, 1955), was applied to the data for each octant. Sample sizes for each octant varied from 19 for the ESE octant to 119 for the NNW octant without the cloud and from 22 for the ESE octant to 111 for the NNW octant with the cloud. It was found that for τ_{500}, test values for all octants exceeded the critical value of ±1.96 except for the ESE octant, for which it was 0.65. For the diffuse/direct ratio, all values were greater than ±1.96. Results of the tests indicate that, except for τ_{500} in the ESE octant, the differences of the means shown in the figures are statistically significant. For both variables, furthermore, the largest test values were for the NNW octant and the smallest were for the ESE octant. Respectively, these were 47.7 and 0.65 for τ_{500} and 18.9 and 3.62 for the diffuse/direct ratio.

Effects of wind direction and precipitable water on the Ångström turbidity coefficient β for $\lambda = 500$ nm and the size distribution parameter α are shown in Figs. 3a and the 3b, respectively. Precipitable water is used as an independent variable because it can make a significant contribution to β, particularly for low turbidity (Malm et al., 1977). Figure 3a shows average values of β against precipitable water for wind directions between 315° and 45°, labeled north wind, and for directions between 135° and 225°, labeled south wind. Triangular and square symbols denote data with and without the volcanic cloud, respectively, and the number near each symbol is the sample size.

It can be noted that for a north wind, $\bar{\beta}$ for precipitable water less than 1 cm is about 0.08 without the cloud and 0.17 with it. For a south wind, $\bar{\beta}$ is 0.09 without the cloud and 0.16 with it. For both directions, the changes in β reflect the large increase in particle concentrations with the cloud. Equivalent graphs for α in Fig. 3b show that for precipitable water less than 1 cm, $\bar{\alpha}$ with the cloud is about 35% smaller than without it for both wind directions and about 30% smaller for a north wind than for a south wind. Both decreases are the result of increases in the number of larger particles. They are associated with the volcanic cloud in the first case and with a north wind in the second. For a south wind without the cloud, it can be noted that $\bar{\alpha}$ is about 1.3, which is the value proposed by Ångström as a representative average. Important effects of a range of zenith angles from 26° to 70° and a range of τ_{500} from 0.03 to 0.6 are inherent in these results.

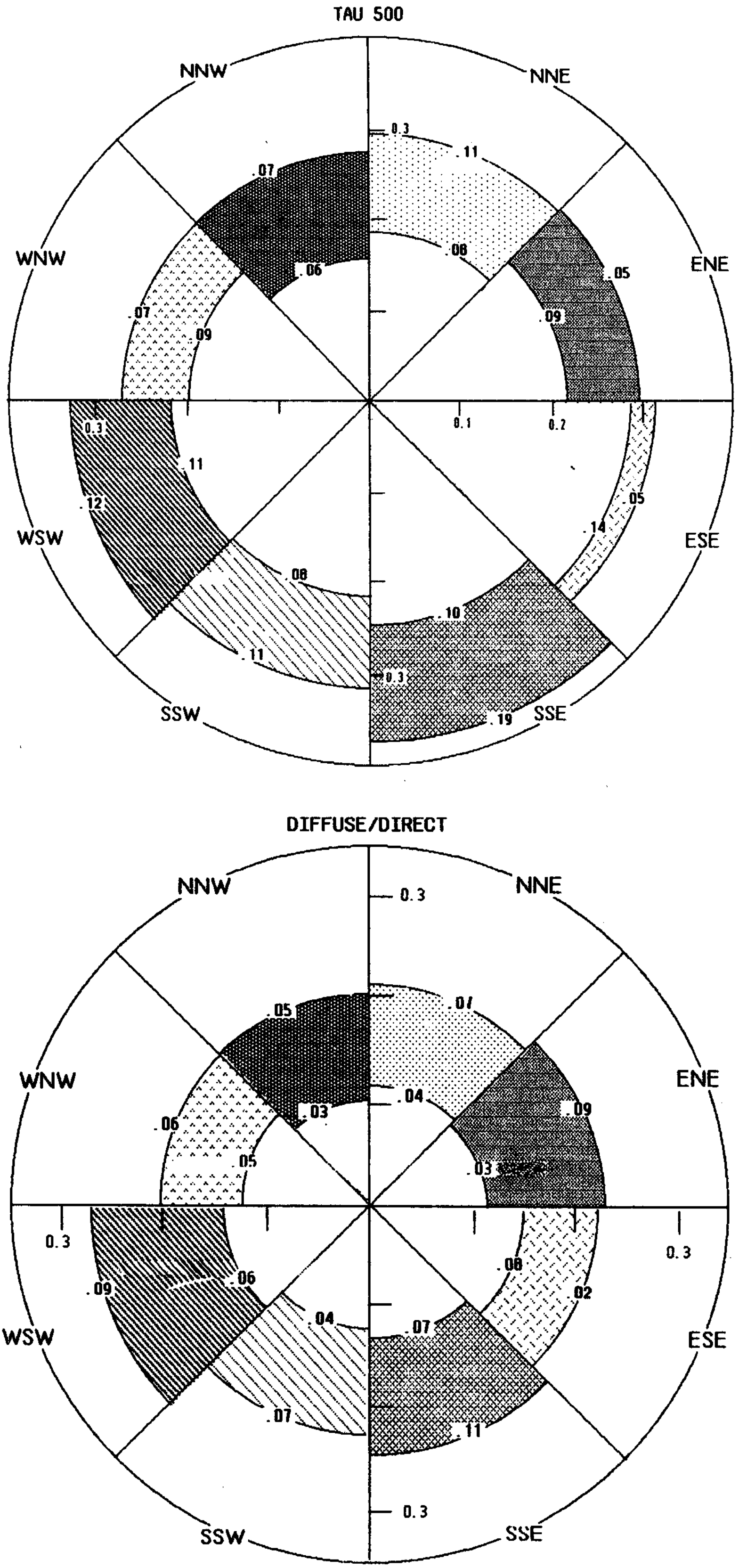

FIG. 2 (a). Average values of 500 nm optical depth in octants of wind direction without (inner arcs) and with (outer arcs) the El Chichón volcanic cloud. The numbers within each arc are standard deviations. (b). As in (a) except that average values of the ratio of diffuse to direct irradiance are on the radii.

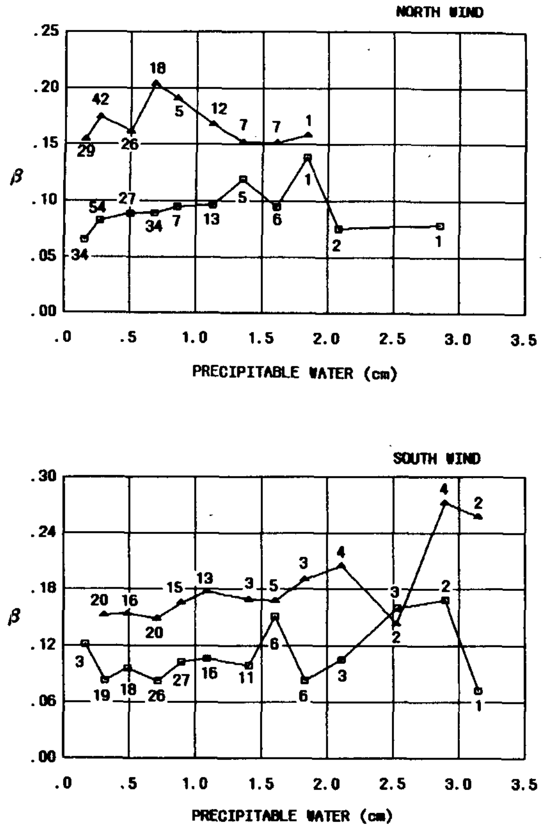

FIG. 3a. Variation of β for $\lambda = 500$ nm in the Ångström turbidity equation with precipitable water for a north wind (top) and a south wind (bottom) with (triangles) and without (squares) the volcanic cloud.

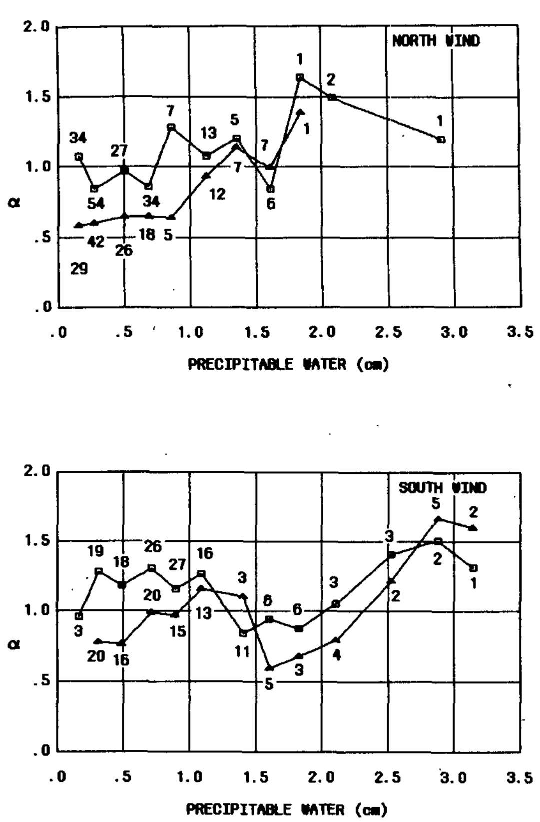

FIG. 3b. As in (a) except that the ordinate is the exponent α in the Ångström turbidity equation.

The effects of different wind directions on irradiances and turbidity parameters that were found are caused by aerosol characteristics mainly within the atmosphere's first 2 km (Tomasi, 1982; Hanel and Bullrich, 1976). Hanel and Bullrich found that the contribution of the first kilometer to the total optical depth is larger than 55% and that it increases with increasing relative humidity near the earth's surface. For the location of the University of Michigan measurement facility, compared to winds from northerly directions, boundary-layer winds from southerly directions contain more water vapor, sulfurous and mixed gases, and particulates of natural and anthropogenic origin. These are the result of air trajectories that, in many cases, include the Gulf of Mexico and the highly industrialized areas of the Ohio or Mississippi valleys. The concentrations of these turbidity constituents with south winds were sufficient not only to mask effects of the volcanic cloud in many cases, but also to produce large variability in the measurement of these effects.

Effects of local aerosol sources occurred with a wind direction in the ESE octant and are evident in Figs. 2a and 2b. For wind directions near an azimuth of 100°, for example, turbidity constituents were advected from the industrialized area of Detroit located 65 km from the measurement site. Weber and Baker (1982) describe a 140% increase in both the diffuse/direct irradiance ratio and τ_{500} for the site that was caused by a gradual shift in wind direction from northeast to east-southeast in one day. Such an increase in turbidity in one day is quite common and is associated with a migratory high-pressure system that produces a cloudless sky and remains north of the measurement site as it moves eastward. A less serious local source of turbidity is the metropolitan area of Ann Arbor, located west-southwest of the site.

Air arriving at the measurement site from a north sector, on the other hand, usually has a long trajectory over remote areas of Canada and, compared to a south wind, has not encountered major sources of turbidity constituents. As a result, the smallest and least variable turbidity is usually observed. Turbidity and irradiance characteristics measured with a north wind without a volcanic cloud, therefore, are considered to be the most representative of those of a clean background aerosol. Quantitatively, these results are probably site-specific, but qualitatively, they apply to the eastern half of the United States and to other locations. Similar values of α and β were obtained by Hallaron (1982), for example, in case studies for various synoptic weather conditions in San Antonio, Texas, and by Tomasi (1982) for locations in Italy.

4. Changes in solar irradiances

There were 22 cloudless days for the period from 26 October 1982 through mid-June 1983 for which daily totals of measured solar irradiances, regardless of wind direction, were compared with those representative of average conditions with low turbidity. Except for diffuse irradiance, the cloud caused a decrease in each measured irradiance. Average percentage changes in daily totals were global (280–2800 nm), −5; global (630–2800 nm), −1; south-facing 42.3°-inclined, −5; direct normal, −24; and diffuse, +87. These changes are similar to those found by Rao and Takashima (1985). For individual days with similar zenith angles and precipitable water but with values of τ_{500} as large as 0.35, the direct normal component decreased as much as 30% compared to average conditions and the diffuse component doubled. Because changes in these two irradiances were in the opposite sense, however, global irradiance, comprised of both, decreased about 6%. Whereas the normal ratio of global filtered (630–2800 nm) to global was 59% without the cloud, the ratio for the volcanic period was 65%. Apparently, an effect of the larger particle sizes comprising the cloud was to increase the energy in the 630–2800 nm spectral interval relative to that in the 280–2800 nm interval.

5. Summary and conclusions

A comparison of solar irradiances and Ångström turbidity parameters measured before and after the arrival of the main stratospheric volcanic cloud from El Chichón on 26 October 1982 showed that the strongest effects of the cloud occurred between 26 October 1982 and mid-June 1983. Categorizing the irradiances and turbidity according to octants of wind direction measured at 30 m showed that only for boundary-layer winds from northerly directions were observed changes the largest and most representative of those caused by the El Chichón volcanic cloud. For a north-northwest wind, τ_{500} increased 87% (from 0.15 to 0.28), the ratio of diffuse to direct irradiance increased 103% (from 0.10 to 0.21), the Ångström wavelength exponent decreased from near unity to 0.6, and the turbidity coefficient increased from 0.08 to 0.17. For an east-southeast wind, τ_{500} increased only 8% (from 0.29 to 0.31), the ratio of diffuse to direct irradiance increased 48% (from 0.15 to 0.22), the Ångström wavelength exponent decreased from 1.3 to 0.9, and the turbidity coefficient increased from 0.09 to 0.16. The larger percentage changes with a wind from a north sector were due to the upper midwest location of the measurement facility in relation to local and distant sources of turbidity constituents.

Average percentage changes in daily irradiance totals regardless of wind direction for cloudless days in the eight-month period were direct normal, −24; diffuse, +87; global (280–2800 nm), −5; global (630–2800 nm), −1; and south-facing 42.3°-inclined, −5.

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