Effects of the El Chichón Volcanic Cloud on Direct and Diffuse Solar Irradiances

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ABSTRACT

Direct normal and diffuse solar irradiances and 500 nm aerosol optical depths measured at the University of Michigan departed far from normal on 26 October 1982, when it is concluded that the main stratospheric cloud from the El Chichón volcanic eruption arrived at the 42°N latitude of the radiation measurement facility. For clear-sky data analyzed through 19 January 1983, direct solar is about 25% less than normal and diffuse solar is about 85% greater. For the same aerosol optical depths and solar zenith angles, the ratio of diffuse to direct is about 30% greater for about 0.3 cm of precipitable water but nearly the same for 0.9 cm. Aerosol optical depths are nearly three times greater for wind directions that naturally advect the cleanest air. The effect of circumsolar irradiance on the methods used to measure direct normal and diffuse irradiances cause the former to be overestimated and the latter to be underestimated.

1. Introduction

The El Chichón volcanic eruption presents a unique opportunity to obtain quantitative information on the effects of a major volcanic eruption on the earth's radiation regime. The additional aerosol burden caused by the stratospheric volcanic cloud is causing large changes in the direct and diffuse solar irradiances. The direct solar irradiance is much less than normal and the diffuse is much greater. The magnitude of these irradiance changes and the net effect on the earth's radiative exchange can be accurately assessed only if effects of the volcanic cloud are isolated from anthropogenic and other effects. The purpose of this paper is to describe the changes in direct and diffuse irradiance caused by the volcanic cloud and to assess them in terms of measurements of aerosol optical depth and atmospheric water vapor content.

2. Irradiance and turbidity measurements

The Michigan Solar Energy and Meteorological Measurement facility is one of eight similar facilities in the United States that was established in 1977 with grants from the U.S. Department of Energy. Since 1979, quality controlled one-minute values of seven solar and atmospheric irradiances and six meteorological variables have been recorded on an automatic data acquisition system. Semi-annual radiometer calibrations and continuous application of quality control programs produce a data set accurate to ±2%. The irradiance sensors are listed in Table 1. In addition, precipitable water and aerosol optical depths at 500 and 880 nm for various optical air masses are obtained with a Volz sun photometer on cloudless or nearly cloudless days. There have been 125 such days for this location during the period August 1979 to January 1983. A data set was constructed that consists of one-minute values of global, diffuse, and direct irradiances and wind direction that coincide with each sun photometer measurement.

On 26 October 1982 an abrupt departure from normal cloudless sky irradiances occurred that clearly exceeded the natural variability. An examination of daily totals of direct and diffuse irradiance indicated that the diffuse irradiance increased by 88% while the direct decreased by 30%. In order to examine this and subsequent changes which we associate with the arrival of the volcanic cloud, the data set was divided into two discrete periods of time. The first period (I) extends from 6 August 1979 to 25 October 1982 and contains 155 data points. The second period (II) extends from 26 October 1982 to 19 January 1983 and contains 100 data points. Most of the data obtained during Period II were for an optical air mass greater than 2.0 due to the time of year. Data for Period I were chosen to correspond to the solar zenith angle range for the data in Period II, which was 64° to 66°.

The diffuse irradiance is measured with a solar-tracking occulting disc that shades a horizontal pyranometer. The disc is 5 cm in diameter and is attached to an arm curved in a 1.15 m arc of a circle with a radius of 0.5 m. The arm rotates about an axis parallel to the earth's polar axis every 24 h. The disc subtends an angle of 5.7° with respect to the field of view of the pyranometer. This is the same field of view of the pyrheliometer used to measure direct normal irradiance.

Because the solar disc is only about 30 min in diameter, the occulting disc excludes a portion of the forward scattered irradiance component and causes

TABLE 1. Irradiance measurements and sensors.

Irradiance	Sensor
Global solar (280–2800 nm)	Eppley* Precision Spectral Pyranometer (PSP)
Global solar (630–2800 nm)	Eppley PSP with RG2 filter
Latitude-angle solar** (280–2800 nm)	Eppley PSP with horizon shield
Diffuse solar (280–2800 nm)	Eppley PSP with occulting disk
Direct normal solar (280–4500 nm)	Eppley Normal Incidence Pyrheliometer (NIP)
Ultraviolet solar (280–390 nm)	Eppley UV photometer
Atmospheric (4500–50 000 nm)	Eppley Precision Infrared Radiometer (PIR)
Sunshine duration	Campbell-Stokes recorder

* Eppley Laboratory, Inc., Newport, RI.

** Irradiance on a south-facing surface inclined from the horizontal at the 42.3° latitude angle of the measurement facility.

measured diffuse to be underestimated. The direct normal irradiance is overestimated because it includes the actual direct plus a forward scattered component, or circumsolar irradiance. It can be defined (Grether *et al.,* 1981) as

$$CS = \int_{\Omega_r}^{\Omega_s} I(\theta, H_2O, \tau_{500}) d\Omega,$$

where Ω_r is the solid angle of the sun and Ω_s is that for the pyrheliometer's field of view. The magnitude of circumsolar irradiance (CS) depends on the solar zenith angle (θ), amount of water vapor (H_2O), and aerosol optical depth (τ_{500}).

3. Aerosol and water vapor effects

Effects of aerosols and water vapor on measured irradiances were assessed with measurements of aerosol optical depth at 500 nm and 880 nm made with a Volz sun photometer. The photometer has a field of view of approximately 2° and thus "sees" some of the circumsolar component, which in the worst case overestimates the 500 and 880 nm optical depth by about 4% (Volz, 1974). Determining values of precipitable water requires the optical depth at 940 nm which is due not only to aerosols but also to water vapor absorption. Values were obtained by linearly extrapolating the optical depths obtained for 500 and 880 nm (Shaw, 1983).

Values of precipitable water were determined by comparing the optical depth ratio at 940 nm and 880 nm with the theoretical value the photometer would indicate at the top of the atmosphere (Volz, 1974). It was assumed that at 940 nm water vapor absorption is the primary process attenuating the radiation. The line strengths are large in the vicinity of this wavelength and with the water vapor amounts typically encountered in the atmosphere, the square root absorption approximation is valid. An instrument calibration constant is determined by comparing radiosonde data for precipitable water to those measured with the photometer. To utilize this method for estimating water vapor, it is assumed that throughout the measurement period water vapor is spatially homogeneous.

One should note that in previous studies $\tau_{940} \approx \tau_{880}$ (Volz, 1974). In the data obtained here, however, τ_{940} was found to be sufficiently different from τ_{880} to warrant a correction factor for the values of precipitable water based on the extrapolated τ_{940} value. By taking into account the direct beam attenuation at 940 nm due to aerosols, it is felt that more accurate values of precipitable water are possible. The aerosol correction factor increased measured values by about 3–5%.

The ratio of diffuse to direct irradiance was examined in relation to τ_{500} for a constant zenith angle and two values of water vapor (measured as centimeters of precipitable water). Fig. 1 shows this ratio as a function of τ_{500}. The solid line refers to Period I and the dashed line to Period II. Both periods are for 0.3 cm of water vapor and a solar zenith angle corresponding to an air mass of 2.44. It can be noted that the ratio of diffuse to direct irradiance is about 30% larger after the arrival of the volcanic cloud.

These results can be compared with those in Fig. 2 which is identical to Fig. 1 except for a large water vapor amount of 0.9 cm. The solid line refers to Period I while the three points are for Period II. It is evident that results for the two periods are nearly identical. One reason is that for the time of year covered by the data, the 0.9 cm of water vapor with a clear sky is a high value and usually occurs with winds from a southerly direction. Winds from this direction contain the most water vapor and anthropogenic aerosols and naturally produce the highest ratios (Weber and Baker,

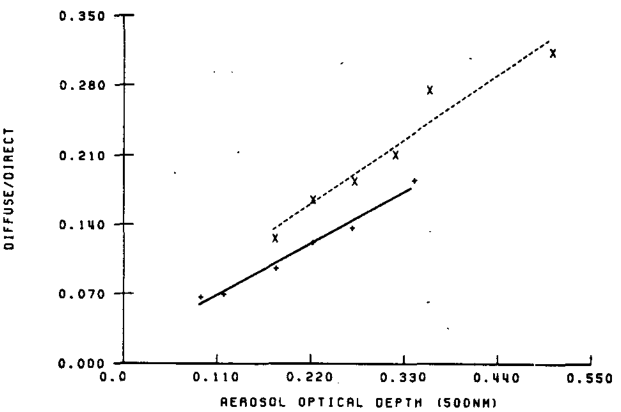

FIG. 1. Measured diffuse to direct irradiance for different aerosol optical depths at a wavelength of 500 nm. The solid and dashed lines refer to Periods I and II respectively. The water vapor amount (measured as centimeters of precipitable water) is 0.3 cm and the air mass is 2.4.

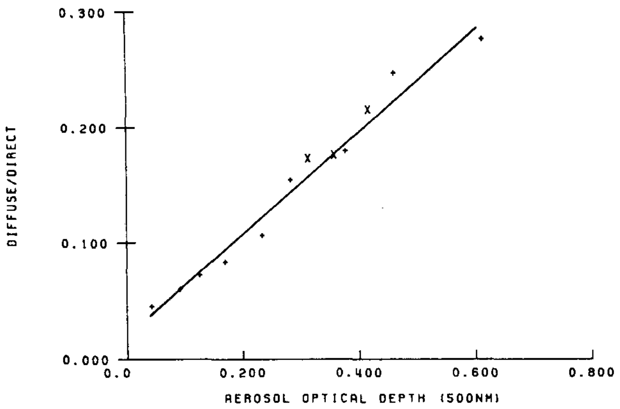

FIG. 2. Measured diffuse to direct irradiance for different aerosol optical depths at wavelength 500 nm. The solid curve is for Period I and the ×s refer to Period II. The water vapor amount is 0.9 cm and the air mass is 2.44.

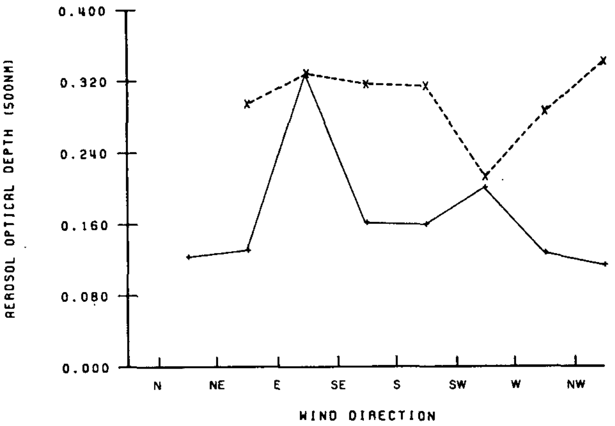

FIG. 4. The aerosol optical depth (500 nm) for various wind directions. The dashed and solid curves are for Periods II and I, respectively. The water vapor amount is 0.9 cm.

1982). The tropospheric aerosol layer and increased water vapor are apparently masking the effect of the volcanic cloud.

One might question whether tropospheric aerosols may be responsible for the large ratio of diffuse to direct after 26 October as shown in Fig. 1. Figs. 3 and 4 show values of τ_{500} vs the 30 m wind direction for 0.3 and 0.9 cm of precipitable water vapor, respectively, for conditions prior to (solid line) and after (dashed line) 26 October 1982. It is evident that $\bar{\tau}_{500}$ is much larger after 26 October for 0.3 cm of water vapor for all wind directions, particularly for north winds that naturally advect the cleanest air, indicating the existence of an additional aerosol layer. For 0.9 cm of water vapor $\bar{\tau}_{500}$ for Period I is near that of Period II for ESE and WSW wind directions as explained previously.

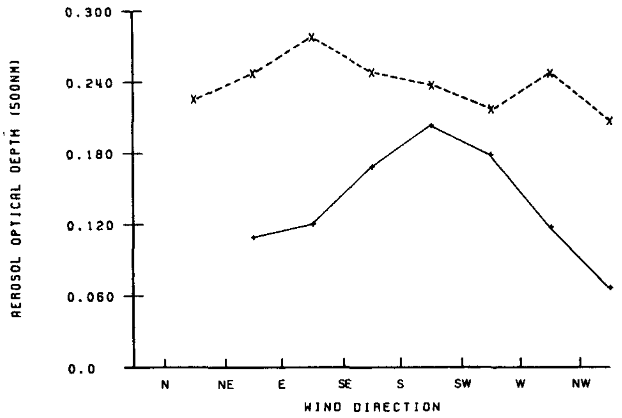

FIG. 3. The aerosol optical depth (500 nm) for various directions. The dashed and solid curves are for Periods II and I, respectively. The water vapor amount is 0.3 cm.

Although water vapor does not absorb radiation at 500 nm, it does influence the aerosol optical depth. For example, an increase in the water vapor from 0.3 to 0.9 cm causes an 18% increase in τ_{500} for Period I and a 20% increase for Period II. Water vapor affects not only the total tropospheric aerosol mass but also the size distribution, both of which influence the circumsolar component.

The circumsolar radiation does influence the measured direct irradiance because of the strong forward-scattered component of the diffuse. Also we are constrained to a large zenith angle which makes the circumsolar component relatively more important than when the sun is high in the sky since, as discussed previously, there is a fixed field of view for measurement of the direct irradiance. This influence of the circumsolar on direct irradiance is seen in the data where, for example, the direct irradiance is about 8% larger after 26 October when the cloud is present, for the same aerosol optical depths (τ_{500} and τ_{800}) and water vapor amount (0.9 cm).

4. Conclusions

We attribute the 20–30% decrease in direct normal irradiance and the 80–90% increase in diffuse irradiance at 42°17′N, 83°45′W from 26 October 1982 to 19 January 1983 to the stratospheric cloud from the El Chichón eruption. Although variable in magnitude, the changes have maintained themselves since then. The ratio of diffuse to direct irradiances increased 25–30% and, for a given optical air mass, depends on water vapor and aerosol optical depth. With southerly winds, tropospheric aerosol often mask the radiative and turbidity effects of the volcanic cloud.

A better approximation to the absolute change in radiation regime is obtainable if a circumsolar correction factor is considered in the measurements of direct and diffuse irradiance. Work is underway to determine the variation of the circumsolar component by calculating the theoretical direct component with measured values of optical depth, water vapor and optical air mass and subtracting it from the measured direct. Only through a continuing analysis of these irradiances obtained in volcanically perturbed and unperturbed atmospheres will it be possible to determine the effective change in the radiation regime due to the El Chichón volcanic cloud.

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