Some Effects of the Yellowstone Fire Smoke Cloud on Incident Solar Irradiance

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ABSTRACT

The influence of the 1988 Yellowstone National Park fire, smoke cloud on incident broadband and spectral solar irradiance was studied using measurements made at the Solar Energy Research Institute's Solar Radiation Research Laboratory, Golden, Colorado.

Results indicate that the smoke cloud's optical depth (at 500 nm) on a smoke-affected day was a factor of 6.3 times greater than on a clear day. The daily total global-horizontal irradiance on the smoky day was 91 percent of that on the clear day. The daily total direct-normal irradiance on the smoky day was 63 percent of that on the clear day. The daily total diffuse sky irradiance on the smoky day was 340 percent of that on the clear day. Analysis of spectral solar irradiance data shows a much more severe attenuation of the shorter wavelengths (UV-visible) than the infrared region.

1. Introduction

Climate models (e.g., general circulation models, GCMs) have been used to predict the effects of increasing "greenhouse gases" and global nuclear war on the earth's climate. The accurate treatment of radiative transfer is a critical element of such modeling. Empirical characterizations of atmospheric radiative transfer are often used to test theoretical approaches and parameterizations used in climate models. This note presents data which describe the radiative transfer effects of greatly increased amounts of particulates (smoke) in the atmosphere.

The Solar Energy Research Institute (SERI) operates a Solar Radiation Research Laboratory (SRRL) on top of South Table Mountain near Golden, Colorado (39°44′33″N, 105°100″50″W), at an elevation of 1829 m (6000 ft). On 29 August 1988, synoptic weather conditions resulted in the transport of the Yellowstone fire, smoke cloud to the eastern slope of the Rocky Mountains in Colorado. This event brought the smoke cloud over the SRRL, which allowed measurements of some smoke cloud effects on incident solar irradiance. By 3 September 1988, the smoke cloud had left and the sky was cloud-free with unlimited visibility.

By comparing the smoke cloud solar irradiance measurements on 29 August 1988, with the cloud-free measurements on 3 September 1988, some of the effects of the smoke cloud were determined.

2. Instrumentation and data

On 29 August 1988 the sky was cloud free from sunrise to 1530 Mountain Standard Time (MST), after which thin cirrostratus clouds formed over the mountains west of SRRL. Horizontal visibility (as reported by an observer) throughout the day was only 15 km, compared to a common visibility of more than 80 km. Smoke from the Yellowstone fire covered the entire sky dome. Winds were from the east-northeast at about 2 m s^{-1} during the daylight hours. The ambient air temperature ranged from a minimum of 12°C at 0600 MST to a maximum of 27°C at 1400 MST. The relative humidity ranged from 12 percent at 1600 MST to 42 percent at 0600 MST.

On 3 September 1988 the sky was cloud free from sunrise to sunset. Horizontal visibility (as reported by an observer) was unlimited all day. The winds were from the north at about 6 m s^{-1} during the daylight hours. The ambient temperature ranged from a minimum of 12°C at 0600 MST to a maximum of 24°C at 1400 MST. The relative humidity ranged from 10 percent at 1600 MST to 20 percent at 0600 MST.

Identical instrumentation were used on both days to measure broadband solar irradiance. The broadband global-horizontal irradiance was measured with an Eppley Precision Spectral Pyranometer (PSP). Our calibration (traceable to the World Radiometric Reference, WRR) of the PSP established a total measurement uncertainty of ±2.6 percent. The direct-normal irradiance was measured with a Eppley NIP (Normal Incident Pyrheliometer), having a field-of-view of 5°43′30″. Our calibration (traceable to the WRR) of the NIP established a total measurement uncertainty

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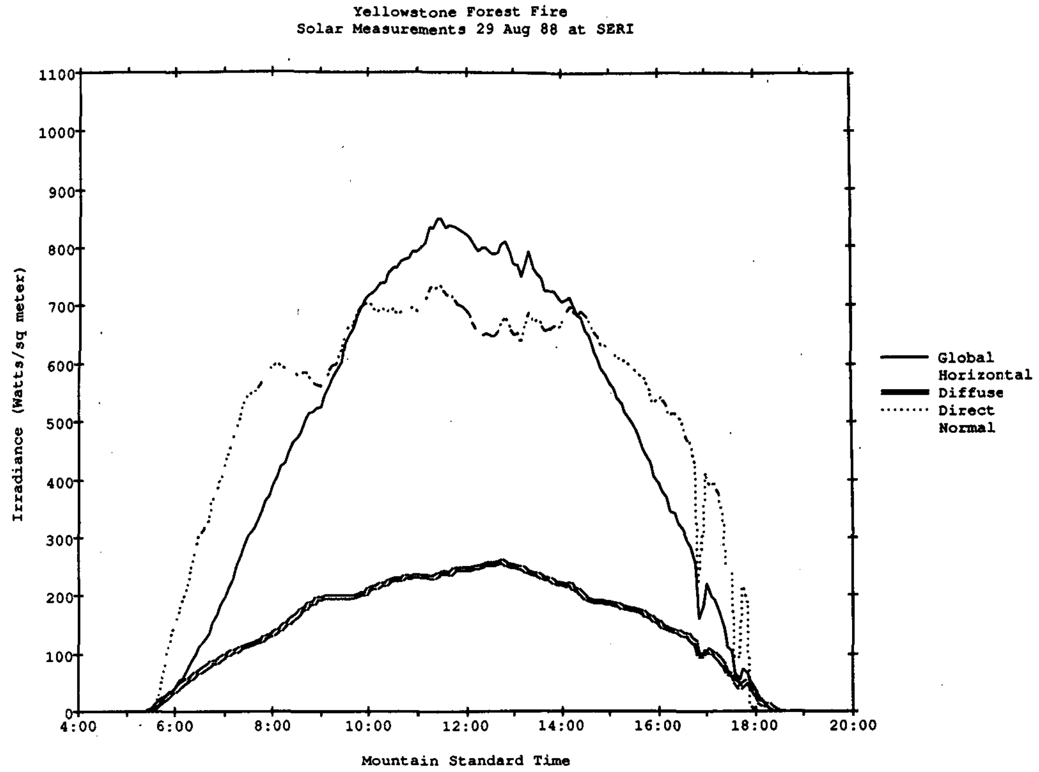

FIG. 1. Broadband global-horizontal, diffuse-horizontal, and direct-normal solar irradiance profiles for the smoke-affected day (29 August 1988), at Golden, Colorado.

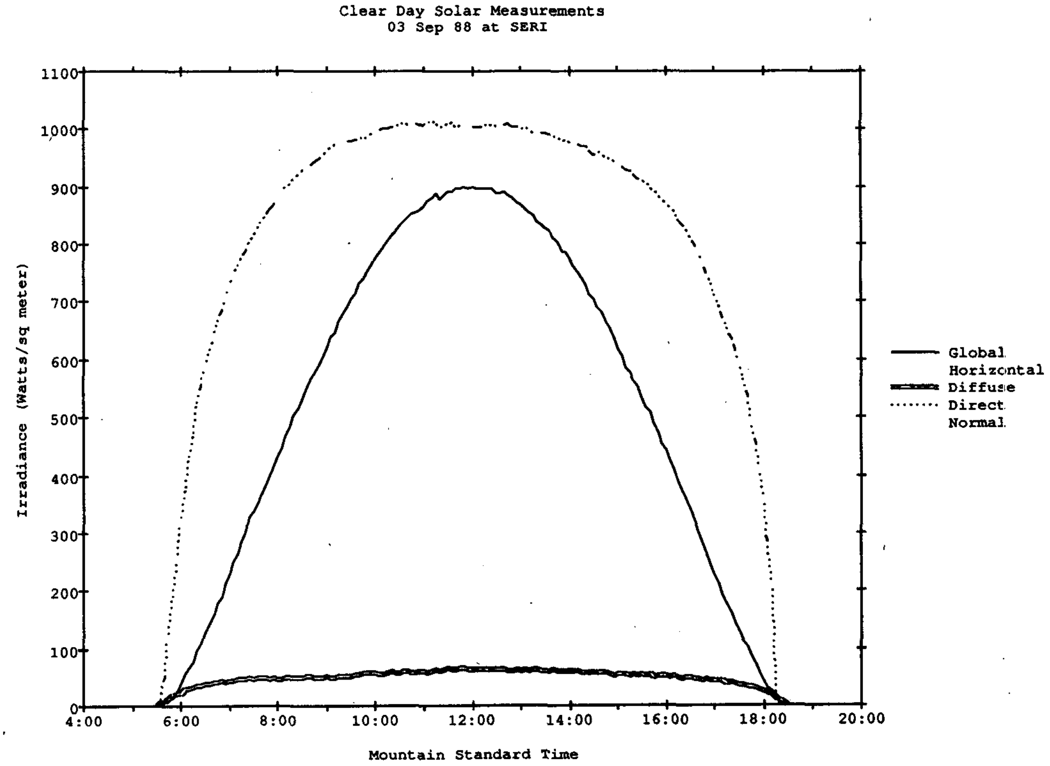

FIG. 2. Broadband global-horizontal, diffuse-horizontal, and direct-normal solar irradiance profiles for a clear day (3 September 1988), at Golden, Colorado.

of ±1.79 percent. The diffuse-horizontal irradiance was measured with an Eppley PSP under a shadowband. We estimate the total measurement uncertainty of the diffuse-horizontal data to be ±5 percent.

Identical instrumentation were used on both days to measure the spectral direct-normal and global-horizontal solar irradiance from 300 nm–1100 nm. The basic spectroradiometer was a LI-COR model 1800, a collimating tube (field of view of five degrees) for direct-normal measurements, and an integrating sphere for the global-horizontal measurements. This instrument has a bandwidth of 6 nm and collects data in 2-nm steps with a wavelength accuracy of ±2 nm. Our (Myers 1989) calibration and characterizations of this instrument established the following total measurement uncertainties.

Measurement Mode	300–350 nm	350–450 nm	450–1050 nm	1050–1100 nm
Global-Horizontal	>±20%	±20%	+5%–12%	+5%–15%
Direct-Normal	>±20%	±20%	±5%	±6%

Global-horizontal and direct-normal spectral solar irradiance scans were taken on both days near true solar noon corresponding to a relative optical air mass of 1.20.

3. Results

The broadband global-horizontal, diffuse-horizontal, and direct-normal temporal profiles for the smoky day and clear day are shown in Figs. 1 and 2, respectively. The reader is left to inspect and analyze the obvious effects of the Yellowstone fire, smoke cloud.

Table 1 lists the effects of the smoke cloud on the broadband global-horizontal, diffuse-horizontal, and direct-normal solar irradiance at true solar noon (relative air mass = 1.20).

Table 2 lists a comparison of the atmospheric transmittance at true solar noon (relative air mass = 1.20) on the smoky day and clear day. The global-horizontal (GH), diffuse-horizontal (DH), and direct-normal (DN) transmittance (T), were calculated by:

$$\mathrm{T\,(GH)} = \frac{\mathrm{GH\ (measured)}}{I_0 \cos\theta_0} \qquad (1)$$

TABLE 1. Comparisons of smoky day and clear day broadband solar irradiance conditions, at true solar noon (relative air mass = 1.20).

Component	Smoky day irradiance (W m^{-2})	Clear day irradiance (W m^{-2})	Ratio smoky/clear
Global-Horizontal	848	901	0.94
Diffuse-Horizontal	258	65.5	3.94
Direct-Normal	735	1,013	0.73

TABLE 2. Comparisons of smoky day and clear day broadband atmospheric transmittance at true solar noon (relative air mass = 1.20).

Component	Smoky day % transmittance	Clear day % transmittance
Global-Horizontal	74.2	79.3
Diffuse-Horizontal	22.7	6.46
Direct-Normal	54.8	75.4

$$\mathrm{T\,(DH)} = \frac{\mathrm{DH\ (measured)}}{I_0 \cos\theta_0} \qquad (2)$$

$$\mathrm{T\,(DN)} = \frac{\mathrm{DN\ (measured)}}{I_0} \qquad (3)$$

where θ_0 is the solar zenith angle and I_0 is the extraterrestrial solar irradiance, 1367 W m^{-2} (Wehrli 1985) adjusted for the day of the year (i.e., earth to sun distance).

Table 3 lists a comparison of the daily total broadband irradiance on the smoky and clear days.

Figure 3 shows a comparison of the global-horizontal spectral solar irradiance at true solar noon (relative air mass = 1.20) on the smoky and clear days. Figure 4 shows a similar comparison for the direct-normal spectral solar irradiance. The spectral global-horizontal and direct-normal atmospheric transmittances were calculated similarly to the broadband transmittances (Eqs. 1, 2), except the spectral measurements and spectral extraterrestrial irradiance values were used. Figure 5 shows ratios of the smoky day to clear day global-horizontal and direct-normal spectral transmittances.

Finally, the measured spectral direct-normal irradiance (I_λ) was used to calculate (according to Beer's Law) a total atmospheric (vertical or normal) optical depth (τ) at 500 nm, by:

$$\tau_\lambda = -[\ln I_\lambda / I_0(\lambda)]/\sec\theta_0 \qquad (4)$$

where λ = 500 nm. At true solar noon the smoky day optical depth (at 500 nm) was 0.94, compared to a value of 0.15 for the clear day. This optical depth is made up of components due to ozone absorption, molecular scattering, aerosol (particulate) scattering, and

TABLE 3. A comparison of daily total broadband irradiance on the smoky and clear days.

Component	Smoky day kWh m^{-2}	Clear day kWh m^{-2}	Ratio smoky/clear
Global-Horizontal	6.20	6.85	0.91
Diffuse-Horizontal	2.04	0.60	3.40
Direct-Normal	6.74	10.66	0.63

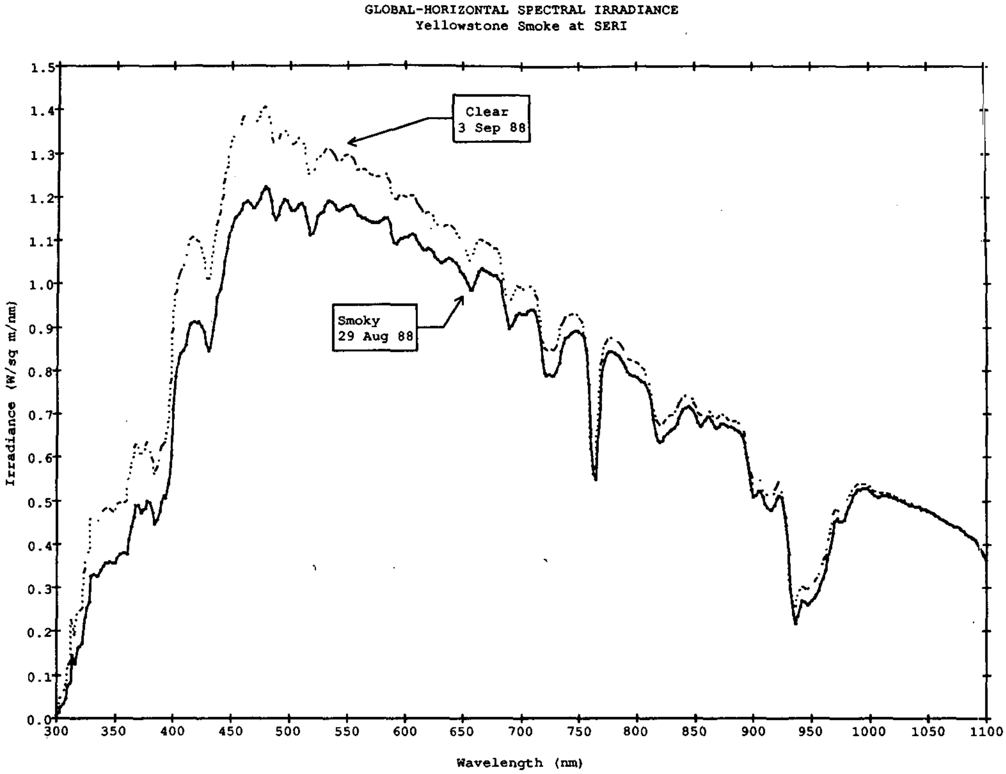

FIG. 3. Global-horizontal spectral solar irradiance profiles for the smoke-affected and clear days at true solar noon (relative air mass = 1.20).

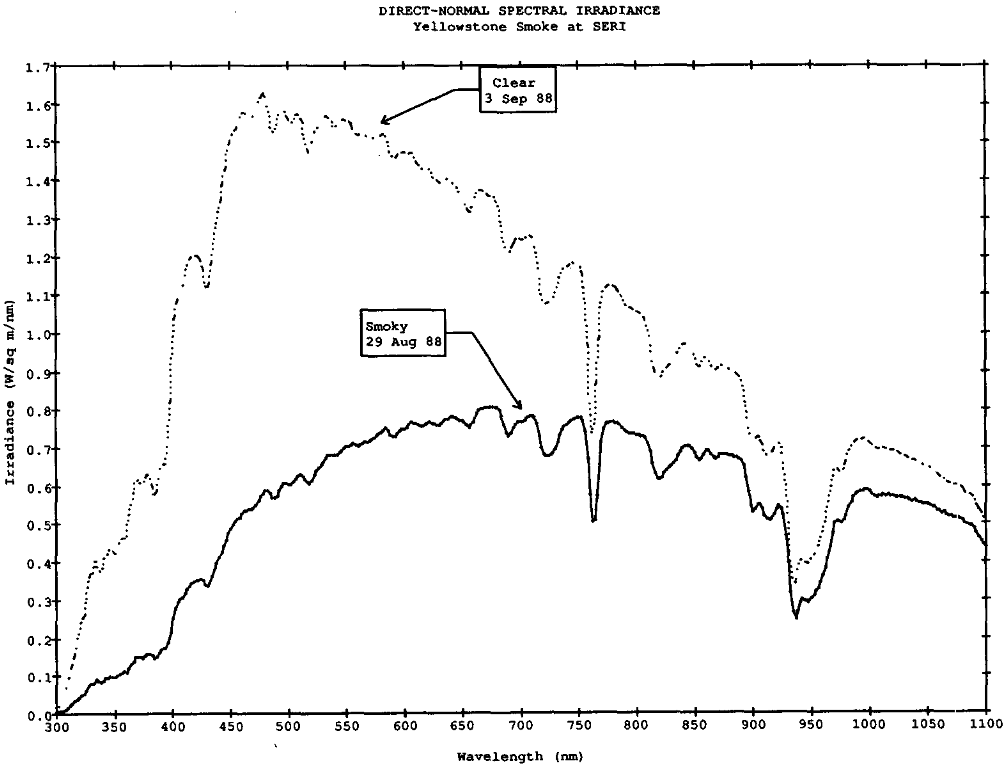

FIG. 4. Direct-normal spectral solar irradiance profiles for the smoke-affected and clear days at true solar noon (relative air mass = 1.20).

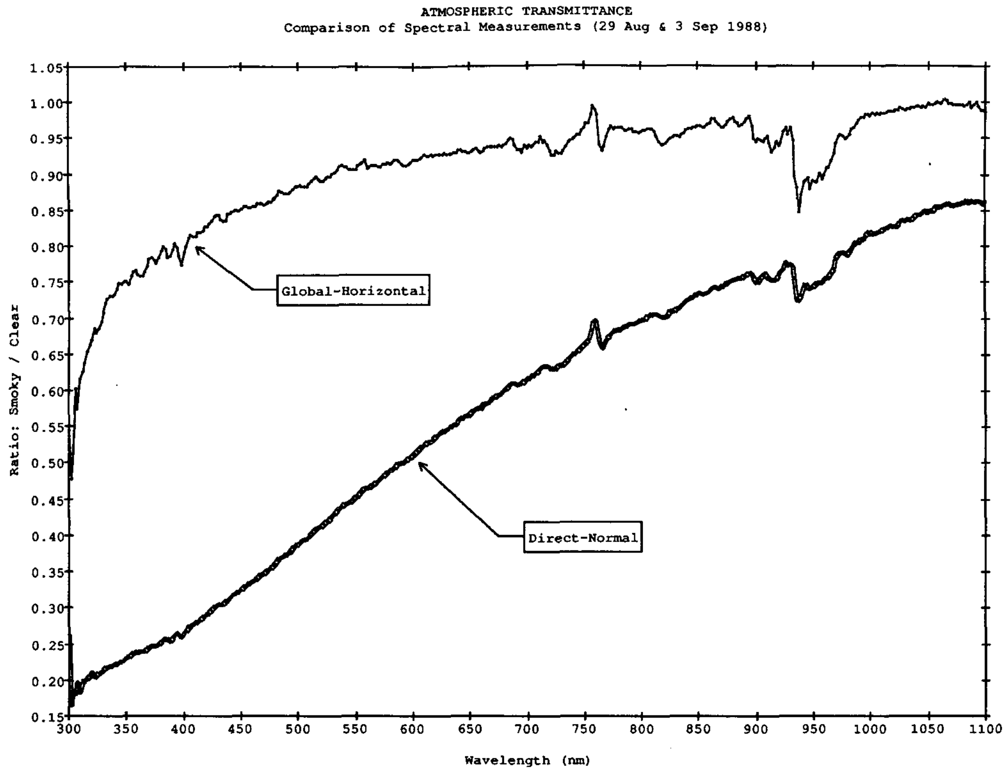

FIG. 5. Ratios of the smoky day/clear day spectral global-horizontal and direct-normal atmospheric transmittances.

any gaseous absorption. Assuming that the molecular scattering, ozone absorption, and gaseous absorption were relatively constant on the smoky and clear days, the increase in total optical depth was due to aerosol (i.e., smoke particulates) scattering and/or absorption.

4. Discussion and conclusions

The comparison of the total optical thickness, at 500 nm, of the Yellowstone fire, smoke cloud and the clear conditions on 3 September 1988, indicate that the 500-nm aerosol optical thickness (sometimes called turbidity) of the smoke cloud was a factor of 6.3 times greater than under the clear conditions. This corresponds to a decrease in vertical atmospheric transmittance (at 500 nm) from 85 percent on the clear day to 32 percent for the smoky day.

Figures 1 and 2 show dramatic effects of the smoke cloud on the broadband solar irradiance conditions. The solar radiation scattered from the direct beam accounts for the sharp increase in diffuse radiation, which compensates for the loss of direct radiation from the global-horizontal irradiance. Qualitatively, this signifies that the smoke particles are fairly efficient scattering centers that compensate for the severe attenuation of the direct-normal irradiance.

The smoke cloud had a severe impact on the direct-normal and diffuse-horizontal broadband irradiance conditions, but had less of an impact on global-horizontal irradiance. Table 3 shows the effects of the smoke cloud on broadband daily total irradiance. The smoke cloud reduces the available direct-normal irradiance to 63 percent of that on a clear day, the global-horizontal to 91 percent of that on a clear day, and the smoke cloud increases the daily diffuse-horizontal irradiance by a factor of 340 percent.

The spectral effects of the smoke cloud, shown in Figs. 3, 4, show a severe reduction in the direct-normal irradiance throughout the ultraviolet (i.e., 300 nm–400 nm), visible (i.e., 400 nm–750 nm) and a lesser impact on the infrared (i.e., 750 nm–1100 nm) irradiance. The global-horizontal irradiance is significantly reduced throughout the UV and visible, but the infrared region is only slightly affected. These characteristics are quantitatively shown in Fig. 5.

Segal et al. (1989) have reported an observational evaluation of the effects of the Yellowstone fire, smoke plume on global-horizontal solar irradiance, the breakup of the surface nocturnal temperature inversion during the morning, and the surface heating in eastern Colorado. They compared the variations in broadband global-horizontal irradiance at eight stations for "smoke affected days" (25 August and 6 September) and "clear days" (23 August and 4 September). They concluded that, in general, the global-horizontal irradiance on the smoke-affected days was only 60 percent–80 percent of the clear day irradiance. Our results (Table 3) show a comparison of 91 percent. Wexler (1950) analyzed the effects of a "smoke pall" on daily global-horizontal irradiance measured at Washington D.C. This smoke cloud was produced by "over 100" forest fires in southwestern Canada. He reported that the daily total irradiance (insolation) under the smoke cloud was only 46 percent of "average clear weather insolation." These comparisons simply point out the high degree of variability of opacity caused by varying amounts of smoke particulates.

Wexler (1950), by comparing the decrease in measured illuminance to the decrease in insolation, concluded that the visible portion of the spectrum was much more attenuated (by the smoke cloud) than the total broadband irradiance. This is in agreement with our spectral results.

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