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DEGRADATION OF SOLAR CONCENTRATOR PERFORMANCE IN THE AFTERMATH OF MOUNT PINATUBO

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Abstract—The Mexican volcano El Chichon and the Philippine volcano Mount Pinatubo injected approximately 6 and 20 million metric tons of SO_2 into the stratosphere, respectively. This, subsequently, produced H_2SO_4/H_2O aerosol of twice the initial mass of SO_2. El Chichon aerosol was confined largely to the northern hemisphere, while Mount Pinatubo aerosol was more evenly divided between hemispheres. Although the Pinatubo aerosol mass was about three times that of El Chichon, it produced less than a triple enhancement in aerosol in the northern hemisphere (the relative increase was 50%) because of this more uniform global spreading. Mount Pinatubo aerosol is shown to have a 15–20% peak extinction effect on direct beam radiation at northern hemisphere sites at 32°N, 40°N, and 46°N. This provides rather convincing evidence that the effect is large at all latitudes in this range and, specifically, that the SEGS performance at 35°N was similarly affected. Volcanic perturbations as large as Mount Pinatubo may produce weather changes that could further impact energy production. Good evidence is presented that weather affected one of the two sites investigated. Based on the close correlation between El Chichon and Mount Pinatubo, we predict the Mount Pinatubo aerosol layer decay pattern over the next year and a half.

1. INTRODUCTION

In private communications with Sandia National Laboratories, the operators of the Solar Electric Generating System (SEGS) parabolic concentrator power plants in southern California at 35°N, Daggett Leasing Corporation, and KJC Operating Company, noted that production was about 30% below normal as a result of a drop in direct solar radiation during the winter and spring of 1992. Their appeal to Sandia to further quantify and, perhaps, predict future insolation levels related to Mount Pinatubo led to the results reported in this paper.

To better illustrate the SEGS plight, consider the schematic in Fig. 1. The area bounded by the rectangle is the total energy needed by the system to generate electricity for the grid during the mid-morning to late evening hours as required by their contract. Before Pinatubo, a large majority of that energy was supplied by solar (upper irradiance curve in Fig. 1), with natural gas providing backup energy during cloudy periods and evening hours. After Pinatubo, the lower irradiance curve is the direct solar contribution, which still represents a large fraction of the needed input energy, but requires that the shortfall be made up by natural gas to an extent that exceeds the limits imposed by the terms of the SEGS contracts. Without a variance that allows more natural gas to be used during the Pinatubo epoch, the SEGS cannot deliver firm power to the grid at the contracted levels.

Sulfur-emitting volcanoes with sufficient force to penetrate the tropopause can have a long-term impact on direct solar radiation. Often the change is minor in comparison to natural seasonal variations, and goes largely unnoticed. The Mexican volcano El Chichon at 17.3°N and the Philippine volcano Mount Pinatubo at 15.1°N are two dramatic exceptions. From satellite instruments it is estimated that El Chichon and Mount Pinatubo deposited 6 and 20 million metric tons of SO_2 in the stratosphere, respectively [1]. Through a series of chemical reactions, the SO_2 is converted to H_2SO_4 and mixed with water to produce an aerosol that is approximately 75% H_2SO_4 by weight [2]. These aerosols are small enough to stay suspended for years until they are removed from the stratosphere by either sedimentation or through tropospheric folding events, where a significant volume of tropospheric and stratospheric air is exchanged. Once the aerosol reaches the troposphere, normal removal processes bring them to the surface, e.g., as rain drops, in a matter of days or weeks.

El Chichon's effects were measurable at midlatitudes for at least three years after its eruption [3]. The peak monthly averaged attenuation was about 11% for visible wavelengths, occurring in the late winter of 1983, 10 months after the eruption. The following winter, following a summer minimum of 4%, it peaked at about 6%, and then it was down to about 3% during the winter of 1985 following a summer minimum of 2%. The method used in that analysis had a noise level of about 1%, which was reached during the winter of 1986.

In this paper we study the effects of Mount Pinatubo at four sites that are at northern mid-latitudes. Our basic approach is to use data bases of global horizontal and direct normal irradiances that include measure-

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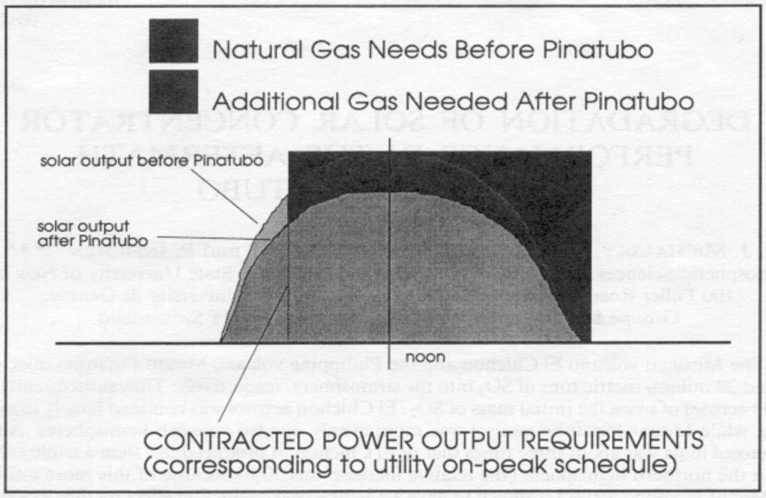

Fig. 1. Schematic of power requirements for SEGS facilities separated into that supplied by solar (before and after Pinatubo) and that supplied by natural gas.

ments before and after the eruption in 1991 June. The four sites are Geneva, Switzerland (46°N); Golden, CO (40°N); Kramer Junction, CA (35°N); and Las Cruces, NM (32°N). The direct data are used to examine the monthly averaged effects of reduced insolation on clear days by aerosol in the stratosphere, and the global horizontal irradiance data are used to determine anomalous weather conditions.

2. DATA ANALYSIS

The direct normal irradiance data were quality checked for sun-tracking errors. All the global horizontal irradiance data from the sites were used without editing. Only data taken within one, two, or three hours of local noon were analyzed. Our procedure required more than a year's data before the eruption of Pinatubo to establish an estimate for the background seasonal irradiance pattern for the site. This background variation pattern is removed from the data, allowing us to focus on variability other than that associated with seasonal phenomena. This assumes that the same monthly averaged irradiance repeats itself each year. The validity of this assumption is discussed for each site. We then used as much data as was available after the eruption to examine the change, if any, in irradiance. We wish to separate the direct Pinatubo effect, i.e., attenuation of direct normal insolation by aerosol, from the effect of weather. To isolate direct effects we used relatively clear days where direct irradiance exceeded a threshold value of 600, 500, or 400 W/m^2 for Las Cruces, Golden, and Geneva, respectively. We did not use the Kramer Junction direct data because of the incompleteness of the record. No threshold was used in comparing global irradiance for indirect effects.

Las Cruces, NM

The time series plot of hourly averages of direct irradiance exceeding 600 W/m^2 and taken within two hours of local noon is given in Fig. 2. Qualitatively, we note a summer minima and winter maxima before the 1991 June eruption and the obvious effects of Pinatubo after that, but a quantitative description is preferred.

A background seasonal pattern for direct irradiance in Las Cruces is assembled in Fig. 3, based on pre-eruption data from 1989 January to 1991 June, by plotting the data as a function of the time of the year they were taken. Zero (0) corresponds to 1 January and one (1) to 31 December. We consider these background data in the sense that the stratosphere was relatively clean throughout this period. An estimate known as locally weighted, robust regression [4] with approximately monthly averaging of direct irradiance appears as the solid line in Fig. 3. The first half-year data are appended and the second half-year data are prepended to the one-year data set to provide a smooth robust estimate at the boundaries. The estimation technique is very sensitive to the local data and may show erratic behavior at the boundaries without this precaution. The direct normal irradiance peaks in late winter and is a minimum in the mid-summer, partially because the solar distance is a maximum and aerosol levels in the summer months are higher. Figure 4 is a plot of the time-series direct data with the seasonal background removed. The robust estimate of monthly averaged deviation in direct irradiance appears as the solid line. In the two and one-half years before the eruption, the departure from background barely exceeds 25 W/m^2, lending credence to our assumption that the seasonal behavior is rather reproducible in the absence of volcanic perturbation. Just after the eruption, the departure exceeds this value by late summer 1991, reaching a maximum depletion in mid-winter 1992 of approximately 150 W/m^2, staying low throughout the spring, and then substantially recovering by summer. This 150 W/m^2 minimum corre-

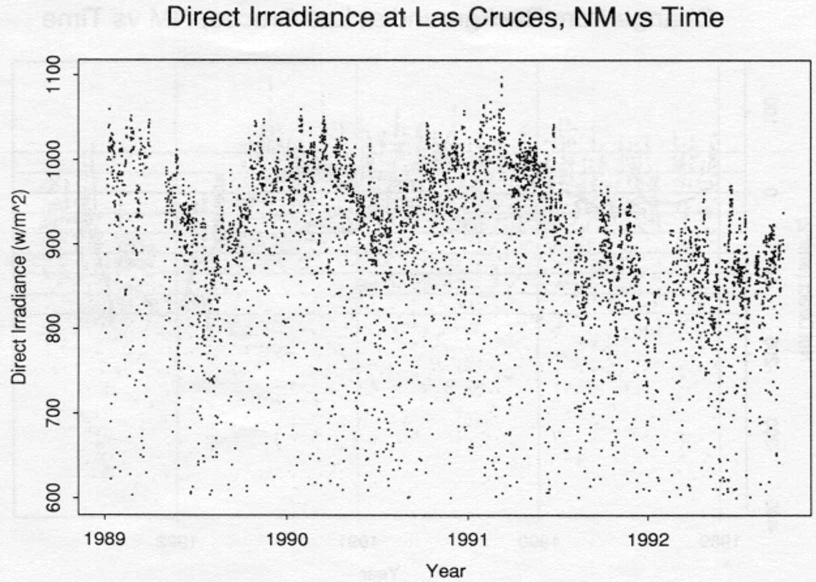

Fig. 2. Time series plot of hourly averages of direct irradiance exceeding 600 W/m^2 within two hours of local noon for Las Cruces, NM.

sponds to a 15% extinction of the 1000 W/m^2 noontime average direct normal irradiance in the winter months. The Pinatubo stratospheric aerosol is expected to scatter 85 to 90% of the attenuated direct beam toward the earth's surface with only 10 to 15% reflected and lost to space, i.e., at peak loading approximately 15 to 22 W/m^2 reduced by the cosine of the solar-zenith angle are lost to the global horizontal irradiance signal.

To study weather effects we examined all of the global horizontal irradiance data using an air mass-independent clearness index, *Kt'*. Perez *et al.*[5] define this as *Kt*, i.e., the ratio of global horizontal to extraterrestrial horizontal irradiance, modified by a term that removes most of the zenith angle dependence. Figure 5 is a plot of the clearness index seasonal background pattern in Las Cruces based on pre-eruption data. The solid line is a robust estimate of the monthly

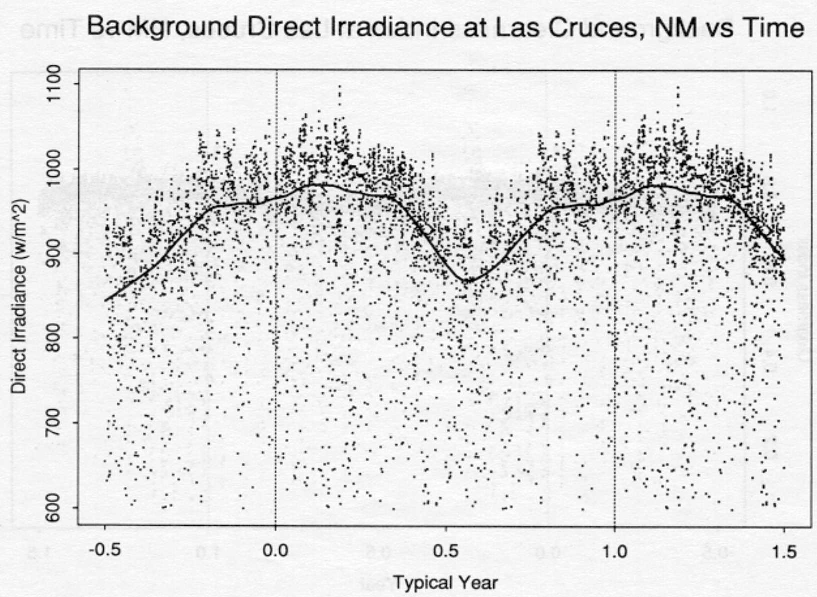

Fig. 3. Overplot of all background data from Fig. 2 before 1991 June onto a single year with zero (0) 1 January and one (1) 31 December of each year. Smoothed line is robust estimate with approximately monthly time resolution.

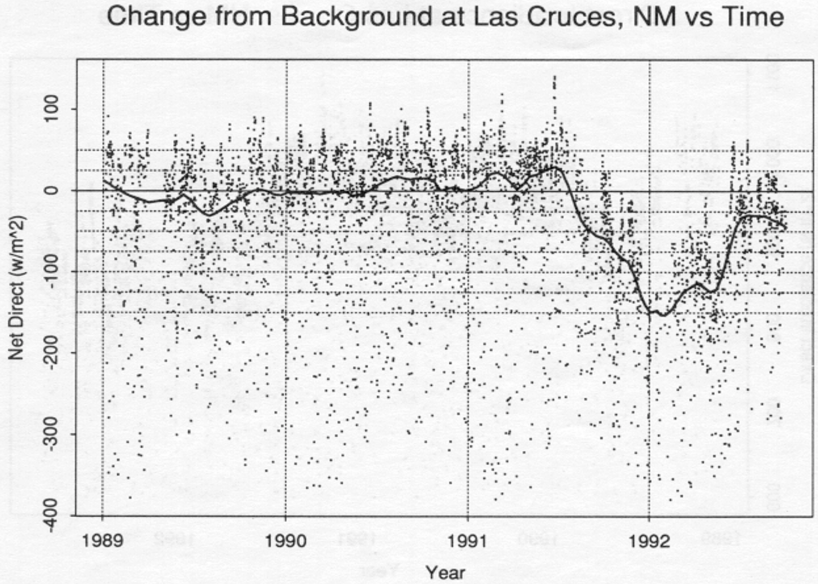

Fig. 4. Time series plot of Fig. 2 with background from Fig. 3 removed according to the time of year the data were measured. Smoothed line is robust estimate of net change with approximately monthly time resolution.

variability in clearness. The clearness has a slight maximum in the spring and is a minimum in the summer, but is rather constant year round. We use this clearness parameter rather than global horizontal irradiance because global horizontal irradiance changes dramatically between summer and winter. The robust estimation technique, which averages over time, could raise the winter estimate and lower the summer estimate because of this large swing; therefore, a normalized parameter is preferred. Figure 6 is a plot of the time series clearness with a background value appropriate for the time of year subtracted. The background period variability in clearness is less than 0.01, and this value is not exceeded until late fall 1991, reaching a minimum in the winter of about 0.045 and recovering to near background values during the summer of 1992. The fractional change

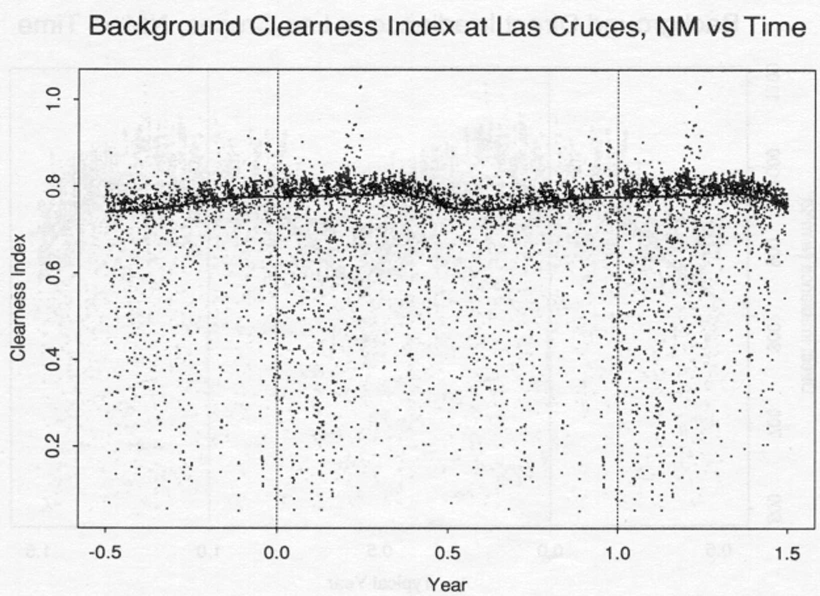

Fig. 5. Overplot of all background clearness index data for Las Cruces, NM, before 1991 June onto a single year with zero (0) 1 January and one (1) 31 December of each year. Smoothed line is robust estimate with approximately monthly time resolution.

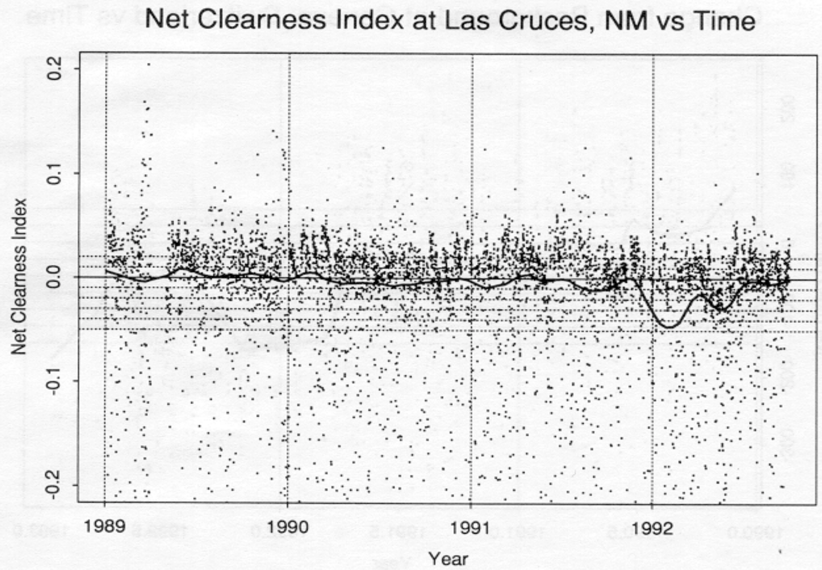

Fig. 6. Time series plot of net clearness for Las Cruces, NM, obtained by subtracting background clearness of Fig. 5 from entire time series of clearness. Smoothed line is robust estimate with approximately monthly time resolution.

in clearness for winter implies a deficit of approximately 35 W/m^2. As explained in the preceding paragraph, about half of this radiation loss can be attributed to reflection from aerosol in the stratosphere. Therefore, we estimate that 15 to 20 W/m^2 is lost because of anomalously bad weather during the middle of the 1992 winter season.

Geneva, Switzerland

Figure 7 is a plot similar to Fig. 3 for a much cloudier site. It contains data taken within two hours of local noon. In Las Cruces there were many totally clear hours of sunshine, as is evident from the clustering of points near the higher solar irradiance values in Fig. 3. In Geneva's case, the threshold was chosen as 400 W/m^2 because totally clear hours are rare there, as seen by the lack of clustering in Fig. 7. There are fewer points because there is one less year of background data and many points fall below the 400 W/m^2 threshold. The peak in background values occurs during the summer and is a minimum during the winter, unlike the Las Cruces pattern. Figure 8 contains the time series data

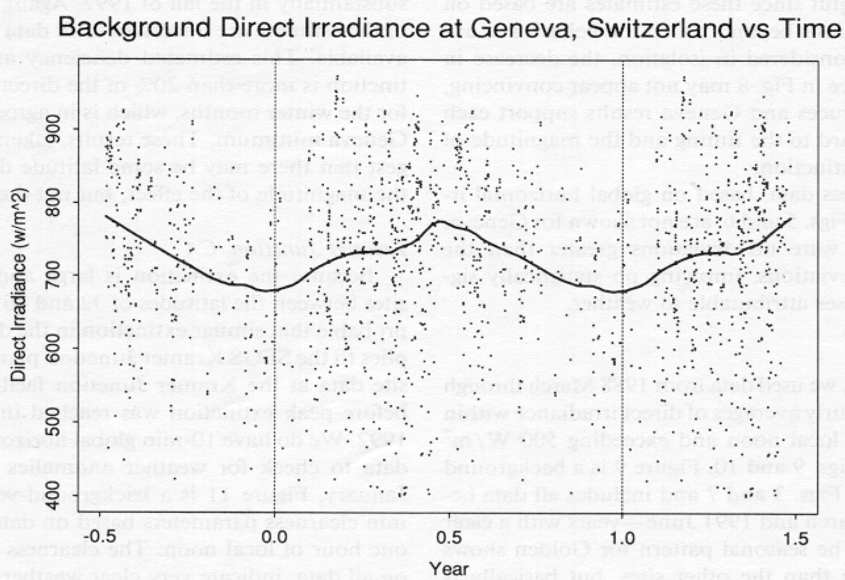

Fig. 7. Same as Fig. 3 except for Geneva, Switzerland, with 400 W/m^2 threshold. Geneva background contains one less year of data than Las Cruces.

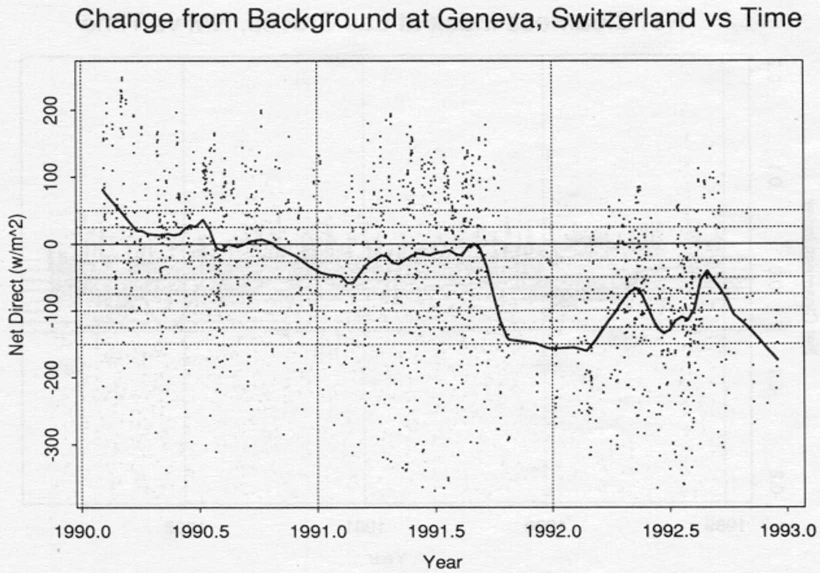

Fig. 8. Time series plot of net direct irradiance with background of Fig. 7 removed according to time of year that data were measured for Geneva, Switzerland. Smoothed line is robust estimate with approximately monthly time resolution.

with the background for the appropriate time of the year removed. The deviation in direct irradiance for the background period is twice as noisy as Las Cruces, with some differences exceeding 50 W/m^2. Nevertheless, the magnitude and phasing of the drop in direct irradiance during the winter of 1992 is consistent with Las Cruces data. For Geneva, this 150 W/m^2 drop represents about a 20% decrease in direct irradiance, although this magnitude is more uncertain than for the Las Cruces data. It should be noted that the beginning and endpoint behavior of the robust fit in Fig. 8 is not meaningful since these estimates are based on data sparse regions beyond which the behavior is undetermined. Considered in isolation, the decrease in direct irradiance in Fig. 8 may not appear convincing, but the Las Cruces and Geneva results support each other with regard to the timing and the magnitude of the volcanic extinction.

The clearness data, based on global horizontal irradiance as in Figs. 5 and 6, are not shown for Geneva, because there were no deviations greater than the background deviations, implying no statistically significant decreases attributable to weather.

Golden, CO

For Golden, we used data from 1988 March through all of 1992. Hourly averages of direct irradiance within three hours of local noon and exceeding 500 W/m^2 were used in Figs. 9 and 10. Figure 9 is a background plot similar to Figs. 3 and 7 and includes all data between 1988 March and 1991 June—years with a clear stratosphere. The seasonal pattern for Golden shows more structure than the other sites, but basically is similar to Las Cruces with a winter maximum and a summer minimum and an overall average about 50 W/m^2 below Las Cruces. Figure 10 is the entire times series with the background removed and a robust estimate through the difference. As for Las Cruces, before 1991 June, the estimate deviates only occasionally by more than 25 W/m^2 from background values. In late summer the deviation exceeded the background noise and reached a minimum coincident with the Las Cruces minimum, but exceeding that site's maximum extinction reaching a low of 200 W/m^2 below background. It recovered some of this loss during the summer, but not to the extent of Las Cruces, and decreased substantially in the fall of 1992. Again, the endpoints of the estimate are uncertain until data from 1993 are available. This estimated deficiency at the peak extinction is more than 20% of the direct beam average for the winter months, which is in agreement with the Geneva minimum. These results, taken together, suggest that there may be some latitude dependence for the magnitude of the effect, but not the timing.

Kramer Junction, CA

Because the extinction is large and consistent at sites between the latitudes of 32 and 46°N, it is highly probable that similar extinction in the direct beam applies to the SEGS Kramer Junction plants as well. On-site data at the Kramer Junction facility terminated before peak extinction was reached in the winter of 1992. We do have 10-min global horizontal irradiance data to check for weather anomalies through 1992 January. Figure 11 is a background-year plot of 10-min clearness parameters based on data taken within one hour of local noon. The clearness pattern, based on all data, indicate very clear weather at all times of the year. Figure 12 is a time-series plot of the change in clearness based on removing the background ap-

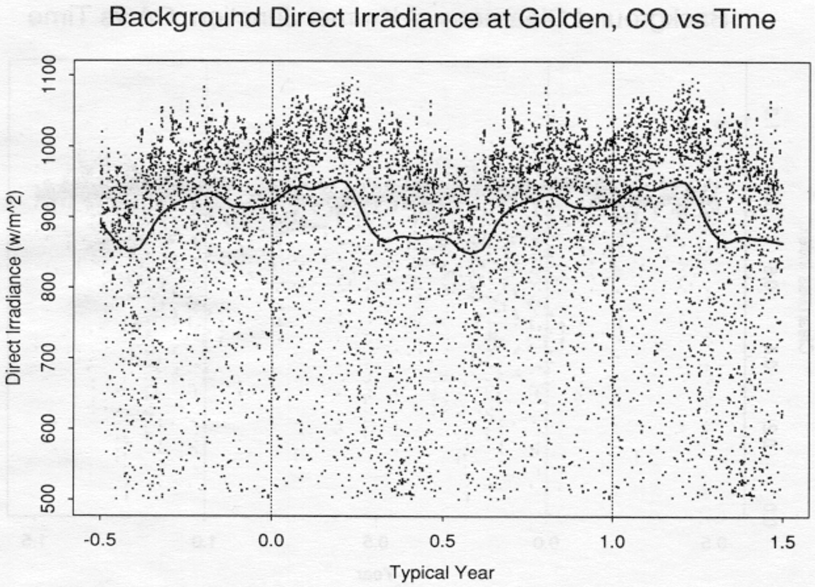

Fig. 9. Same as Figs. 3 and 7 except for Golden, CO, with 500 W/m^2 threshold and hourly averages within three hours of local noon.

propriate for the time of the year. Unfortunately, data gaps create uncertainty that is nearly as large as the dip in clearness following the eruption in late 1991. However, the dip is consistent with the loss in the direct beam caused by stratospheric aerosol, i.e., there does not appear to be additional loss due to a weather anomaly. Again, we can only ascertain this to the limits of the data that end in 1992 January, before the extinction peak noted at the other sites.

3. SUMMARY

All direct irradiance measurements imply a peak extinction in the direct beam radiation at mid-latitudes during the winter of 1992 of 15 to 20%. The overall phasing of the time-dependent extinction is very similar at all sites with some variation in magnitude. We conclude that this direct solar beam extinction behavior applies to all sites between 32 and 46°N, including the

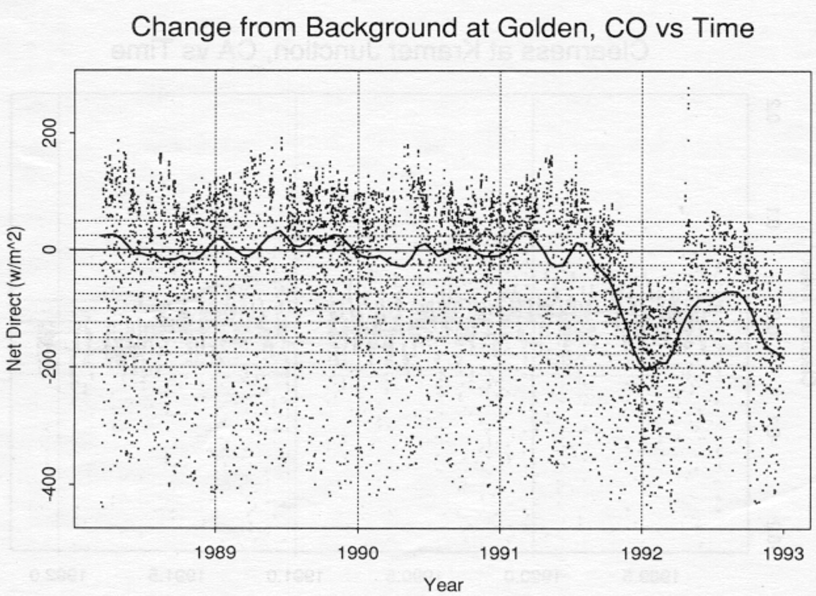

Fig. 10. Time series plot of net direct irradiance with background of Fig. 9 removed according to time of year that data were measured for Golden, CO. Smoothed line is robust estimate with approximately monthly time resolution.

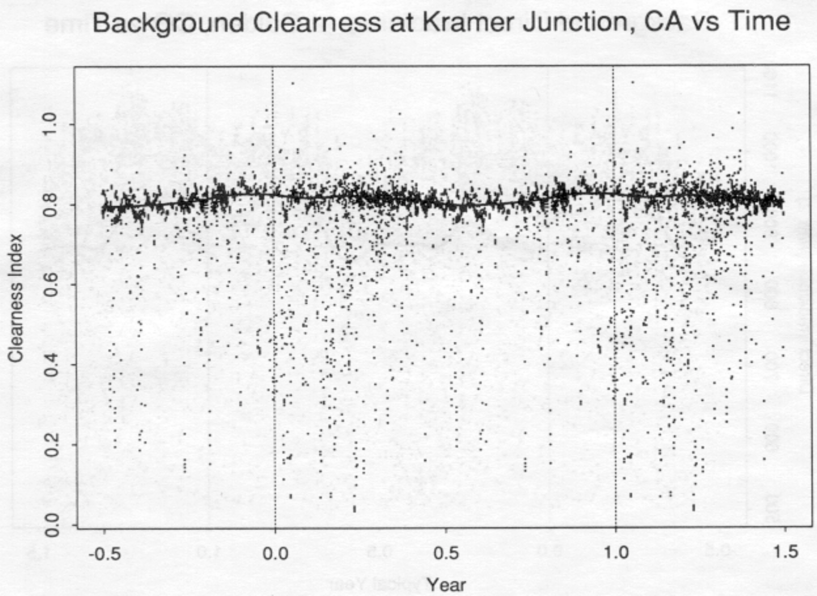

Fig. 11. Same as Fig. 5 except 10-min data within one hour of local noon for Kramer Junction, CA (SEGS site).

SEGS facilities in Southern California. For reasons discussed in Michalsky *et al.*[3], we do not expect this same behavior at tropical and arctic latitudes. Basically, El Chichon extinctions at a tropical site and an arctic site were either not in phase or substantially different in magnitude, respectively. Assuming Pinatubo aerosol follows the same pattern as El Chichon aerosol, which it has for the first one and one-half years following the eruptions[6], we can expect about 10 to 13% extinction this winter (1993), 3 to 4% this summer (1993), and 5 to 7% next winter (1994). The winter extinction recovery, as explained in Michalsky *et al.*[3], is probably caused by wintertime transport from a tropical resevoir, which itself is slowly decreasing. The importance of a long-term, continuous, and well maintained data collection system cannot be stressed enough. The Las Cruces and Golden data sets provided the clearest signal of stratospheric aerosol and weather effects because of the completeness and length of their data records. The clearness parameter used to study climate anomalies

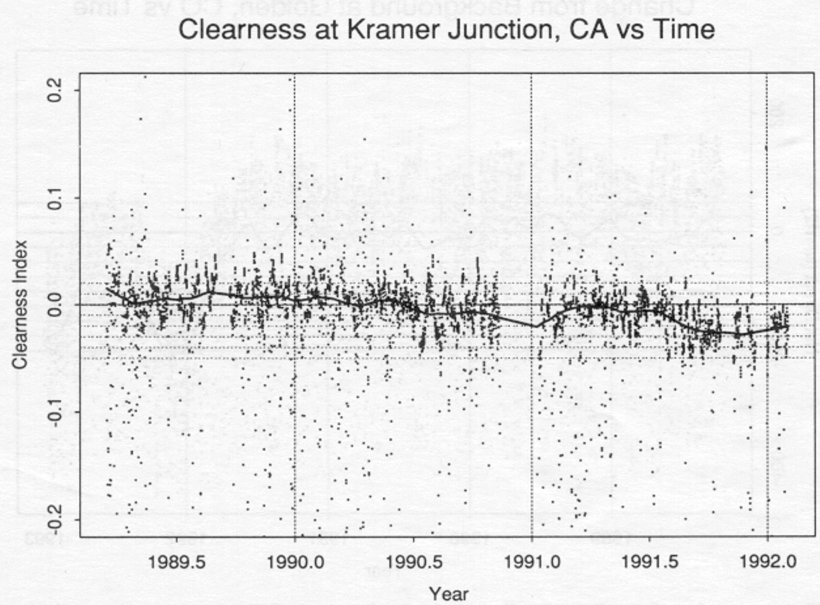

Fig. 12. Same as Fig. 6 except 10-minute data within one hour of local noon for Kramer Junction, CA (SEGS site) and background data of Fig. 11 subtracted.

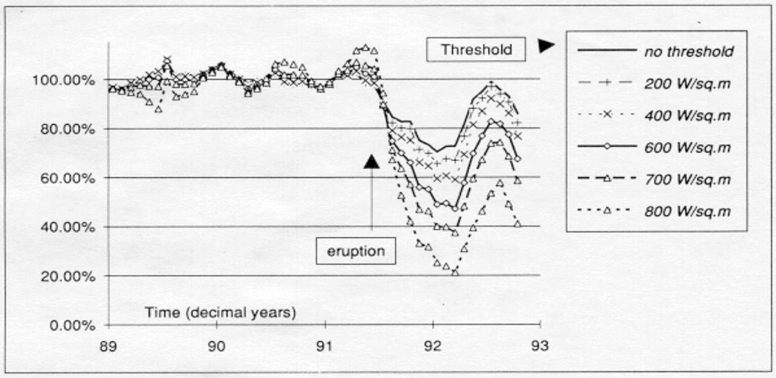

Fig. 13. Plot of direct solar energy loss relative to background and its dependence on operating thresholds for a SEGS-like facility in Las Cruces.

is preferred over global horizontal irradiance when using robust estimation to approximate background signal and remove it from time series data. The clearness parameter normalizes the data so that the robust estimate is not unduly influenced by large variations in nearest neighbors.

The impact of the direct beam reduction on solar thermal power plants is magnified because these plants cannot produce energy until a given direct irradiance threshold is reached. This is illustrated in Fig. 13, which features a plot of useable direct beam energy above a series of thresholds, normalized to a pre-eruption background for the Las Cruces site. Note that the combined effects of stratospheric aerosol extinction and weather reduce the available direct solar irradiance to about the 30% level even without the threshold effect for Las Cruces.

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