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CONCENTRATION SYSTEM PERFORMANCE DEGRADATION IN THE AFTERMATH OF MOUNT PINATUBO

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ABSTRACT

Major volcanic eruptions occur every few years, but most have little effect on solar radiation or climate. However, in the last ten years two volcanoes have decreased solar radiation and influenced weather at a level that might be expected at the frequency of about once a century. The Mexican volcano El Chichon and the Philippine volcano Mount Pinatubo put 6 and 20 million metric tons of SO_2 in the stratosphere, respectively. SO_2 is converted into H_2SO_4, which mixes with water to produce aerosol. Since there is no weather in the stratosphere and the aerosol is small, these aerosol particles remain suspended until coagulation and sedimentation bring them to the troposphere where they are removed by normal wet and dry deposition processes. The extinction in the direct solar irradiance from El Chichon was found to peak during the winter of 1983 at about 11% for northern mid latitudes. Mount Pinatubo's peak extinction during 1992 was about 15%. Data from four northern, mid-latitude sites are examined to compare the direct consequences of the volcano's eruption on the performance of concentrating solar energy systems and the indirect effects that may be associated with Mount Pinatubo's perturbation of the weather.

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, 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, leading to a significant reduction in revenues. Their appeal to Sandia to further quantify and, perhaps, predict future insolation levels related to Mount Pinatubo led to this study and our results reported in this paper.

Sulfur-containing 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 (Bluth et al. 1992). 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. These aerosols are small and can stay suspended for years until they are removed from the stratosphere by either sedimentation after growth through coagulation 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 mid latitudes for at least three years after its eruption (Michalsky et al. 1990). The peak monthly-averaged attenuation was about 11% for visible wavelengths, occurring in the late winter of 1992, about ten 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 technique used in that study 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 measurements before and after the eruption in 1991 June. The four sites are Geneva, Switzerland (46° N); Boulder, Colorado (40° N); Kramer Junction, California (35° N); and Las Cruces, New Mexico (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. In the case of Boulder we used aerosol optical depth at visible wavelengths to compare with traditional solar irradiance data at the other three sites.

2. DATA ANALYSIS

For the three sites with direct normal irradiance--Geneva, Kramer Junction, and Las Cruces--data were quality checked for sun-tracking errors by our software. All the global horizontal irradiance data from the sites were used without editing. Only data taken within two hours of solar noon were analyzed. Our procedure required more than a year's data before the eruption of Pinatubo to establish an estimate for the background annual irradiance for the site. We then used as much data as we could get after the eruption to examine the change, if any, in irradiance levels.

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 or 400 watts/meter^2 for Las Cruces and Geneva, respectively. We did not use the Kramer Junction direct data because of large data gaps. No threshold was used in comparing global irradiance data.

2.1 Las Cruces, New Mexico

A background seasonal pattern for direct irradiance in Las Cruces is assembled in Fig. 1, 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. The data are hourly averages of irradiance acquired within two hours of 12 noon local time. We consider these data background data in the sense that the stratosphere was relatively clean throughout this period. A robust estimate with approximately monthly averaging of direct irradiance appears as the solid line in Fig. 1. 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. Fig. 2 is a plot of the time-series direct data with the seasonal background removed. This assumes that the same monthly-averaged irradiance repeats itself each year. 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 rarely exceeds 25 watts/meter^2. Just after the eruption the departure exceeds this value by late summer 1991 reaching a maximum depletion in mid-winter 1992 of approximately 150 watts/meter^2, staying low throughout the spring and then substantially recovering by summer. This 150 watt/meter^2 minimum corresponds to a 15% extinction of the 1000 watt/meter^2 noon-time average direct normal irradiance in the winter months. The aerosol model for the Pinatubo stratospheric aerosol predicts that 85-90% of the attenuated direct beam is scattered forward toward the earth's surface and only 10-15% is reflected and lost, i.e., at peak loading 15-22 watts/meter^2 times the cosine of the solar-zenith angle are lost to the global horizontal irradiance signal.

To study weather effects we examined all global horizontal irradiance data in a normalized, air mass-independent clearness index form, k'_T, as defined in Perez et al. (1990). Fig. 3 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 variability in clearness. The clearness peaks 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 technique, which averages over time, could be unduly influenced by higher neighbor points in the winter and lower neighbor points in the summer, therefore, a normalized parameter is preferred. Fig. 4 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 in clearness for this time of year implies a deficit of approximately 35 watts/meter^2. As explained in the preceding paragraph, about half of this radiation loss can be accounted for by reflection in the stratosphere. Therefore, we estimate that about 20 watts/meter^2 is lost because of anomalously bad weather during the middle of the 1992 winter season.

2.2 Geneva, Switzerland

Fig. 5 is a plot similar to Fig. 1 for a much cloudier site. In Las Cruces there were many totally clear hours of sunshine as seen by the clustering of points near the higher solar irradiance values in Fig. 1. In Geneva's case the threshold was chosen as 400 watts/meter^2 because totally clear hours are rare there as seen by the lack of clustering in Fig. 5. There are fewer points because there is one less year of background data and many points fall below the 400 watt/meter^2 threshold. The peak in background values occurs during the summer and is a minimum during the winter, unlike the Las Cruces pattern. Fig. 6 contains the time series data with the background for the appropriate time of the year removed. The deviation in direct irradiance for the background period is twice as noisy with some differences exceeding 50 watts/meter^2. Nevertheless, the magnitude of the drop in direct irradiance during the winter of 1992 is about the same as in Las Cruces at 150 watts/meter^2. It should be noted that the beginning and end point behavior of the robust fit is not meaningful since these estimates are based on data sparse regions beyond which the behavior is undetermined. The clearness data, based on global horizontal irradiance as in Figs. 3 and 4, are not shown for Geneva, because there were no deviations greater than the background deviations implying no decreases attributable to weather.

2.3 Boulder, Colorado

In the case of Boulder the data are not irradiance, but aerosol optical depths. The data are acquired on clear days with no cirrus. The data are acquired with a rotating shadowband photometer and reduced to aerosol optical depths following the procedures described in LeBaron et al. (1989). Fig. 7 is a time series plot of the aerosol optical depth with background subtracted. The solid line is the robust monthly-averaged optical depth in volcanic aerosol. The background noise is about 0.01 optical depth with a peak extinction of about 0.15 optical depths at an effective wavelength of 555 nm. To relate this to direct irradiance we note that the loss in energy at this wavelength is given by

$$\text{fractional\_loss} = 1 - \exp(-\text{optical\_depth}).$$

A fourteen percent loss in beam radiation at 555 nm is consistent with the 150 watt/meter^2 losses at the other two sites in view of the uncertainty of each calculation.

Since there is a longer data record following the eruption than at the other two sites, we can see that, following the summer minimum, the extinction increase in the winter of 1993, hinted at in Fig. 2, is confirmed. Since this follows the El Chichon pattern quite well, we expect that Pinatubo will yield a similar extinction pattern for the northern mid latitudes for the next two years with roughly a 50% larger magnitude than El Chichon exhibited.

2.4 Kramer Junction, California

Because the extinction is similar at sites between the latitudes of 32 and 46° N, it is probable that this extinction in the direct beam applies to Kramer Junction and the SEGS plants as well. We have insufficient direct irradiance data at Kramer Junction to confirm this, however. We do have 10-minute global horizontal irradiance data to check for weather anomalies. Fig. 8 is a background-year plot of 10-minute 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. Fig. 9 is a time series plot of the change in clearness based on removing the background appropriate for the time of the year. Unfortunately, data gaps create uncertainty that is nearly as large as the dip in clearness following the eruption. However, the dip is consistent with the loss in the direct beam, i.e., there does not appear to be additional loss due to a weather anomaly. We can only ascertain this to the limits of the data that end early in 1992, before the extinction peak noted at the other sites.

3. SUMMARY

Both direct irradiance (Geneva and Las Cruces) and direct illuminance (Boulder) measurements imply a peak extinction in the direct beam radiation at mid latitudes during the winter of 1992 of approximately 15%. The overall behavior of the time-dependent extinction is similar at all sites. We, therefore, believe that this direct solar beam extinction behavior applies to all sites between 32° and 46° N, including the SEGS facilities in Southern California. For reasons discussed in Michalsky et al. (1990), we cannot expect this same behavior at tropical and arctic latitudes. Basically, El Chichon extinction at a low latitude site and a high latitude site was either not in phase or not of the same magnitude, respectively.

Assuming Pinatubo aerosol follows the same pattern as El Chichon aerosol, which it has to date, we can expect about 10% extinction this winter (1993), 3% this summer (1993), and 5% next winter (1994).

The importance of a long-term, continuous, and well-maintained data collection system cannot be stressed enough. The Las Cruces data set provided the clearest signal of stratospheric aerosol and weather effects because of the completeness and length of its data record.

The clearness parameter used to study climate anomalies 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. 10 that features a plot of useable direct beam energy above a series of thresholds, normalized to a pre-eruption background for the Las Cruces site.

4. ACKNOWLEDGMENTS

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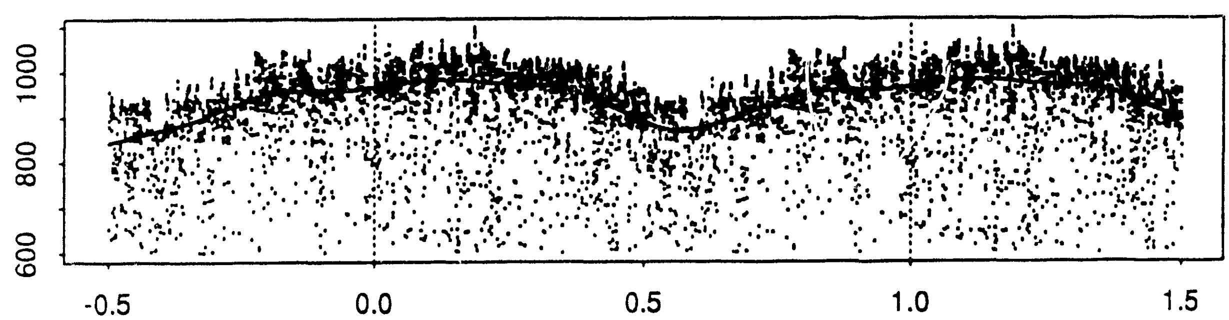

Fig. 1. Background direct irradiance in watts/meter^2 vs time of year for Las Cruces, NM

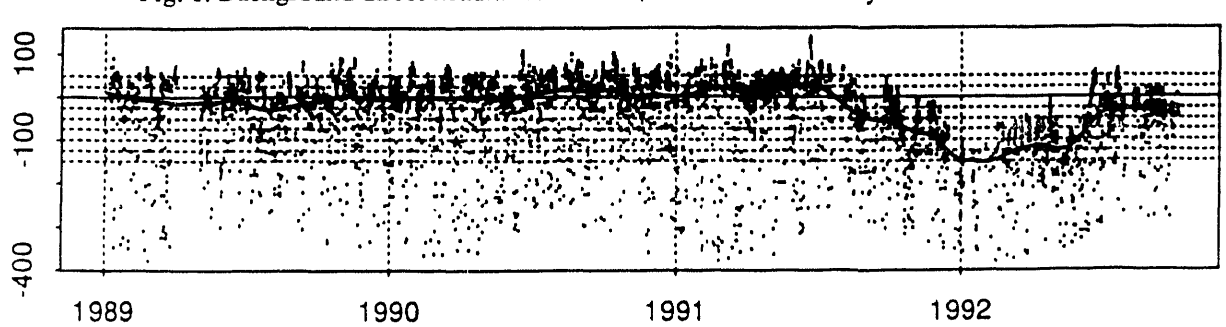

Fig. 2. Net direct irradiance in watts/meter^2 versus time in years for Las Cruces, NM

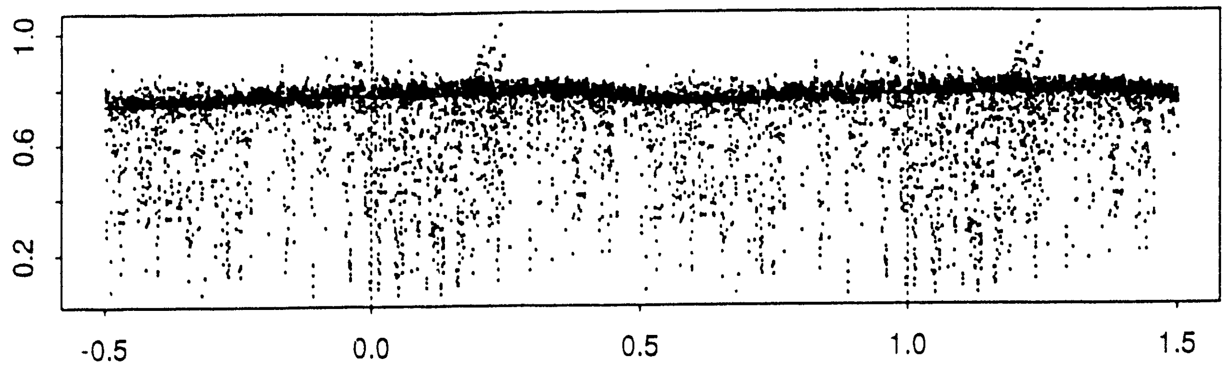

Fig. 3. Background clearness vs time of year for Las Cruces, NM

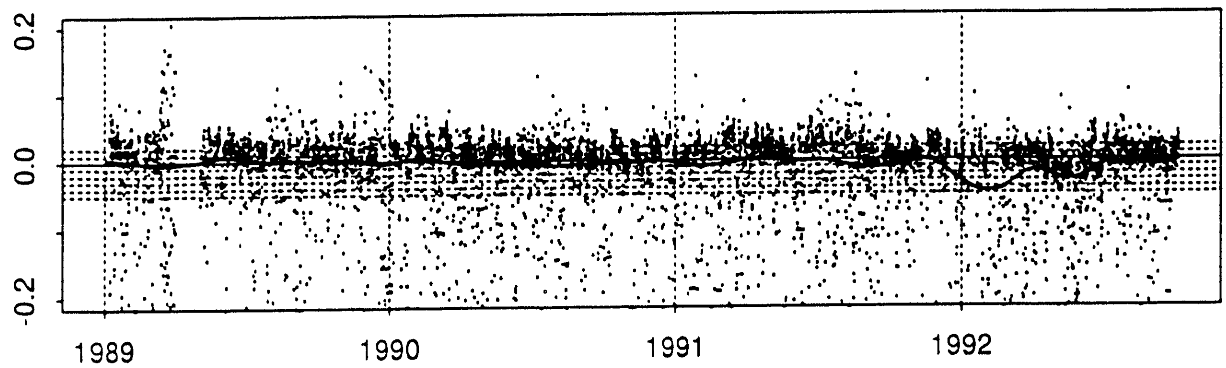

Fig. 4. Net clearness vs time in years for Las Cruces, NM

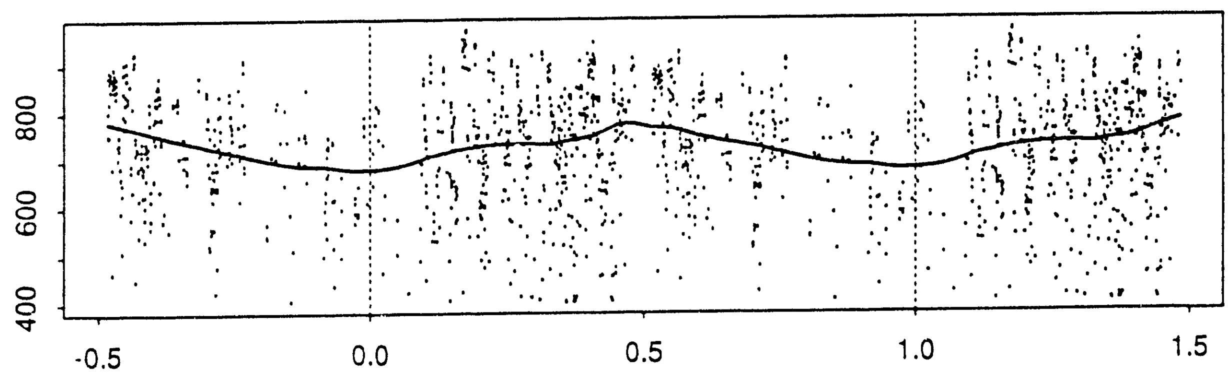

Fig. 5. Background direct irradiance in watts/meter^2 vs time of year for Geneva, Switzerland

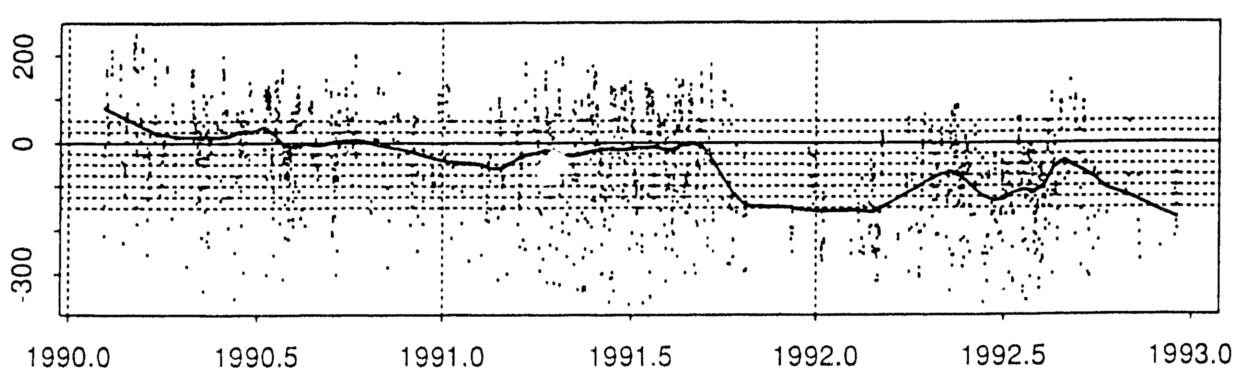

Fig. 6. Net direct irradiance in watts/meter^2 versus time in years for Geneva, Switzerland

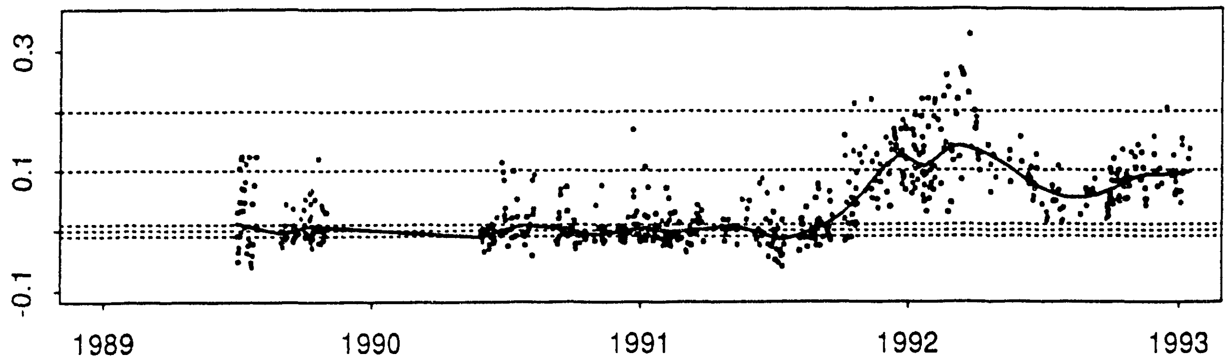

Fig. 7. Net aerosol optical depth at 555 nm vs time at Boulder, CO

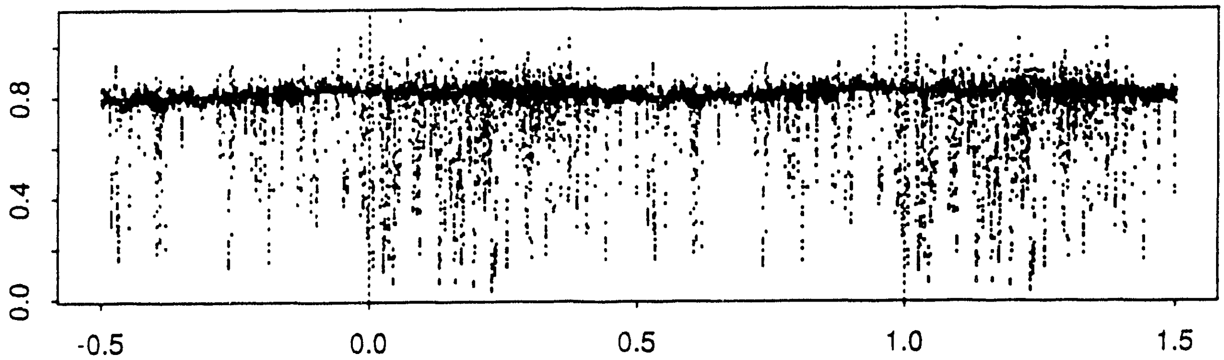

Fig. 8. Background clearness as a function of time of year at Kramer Junction, CA

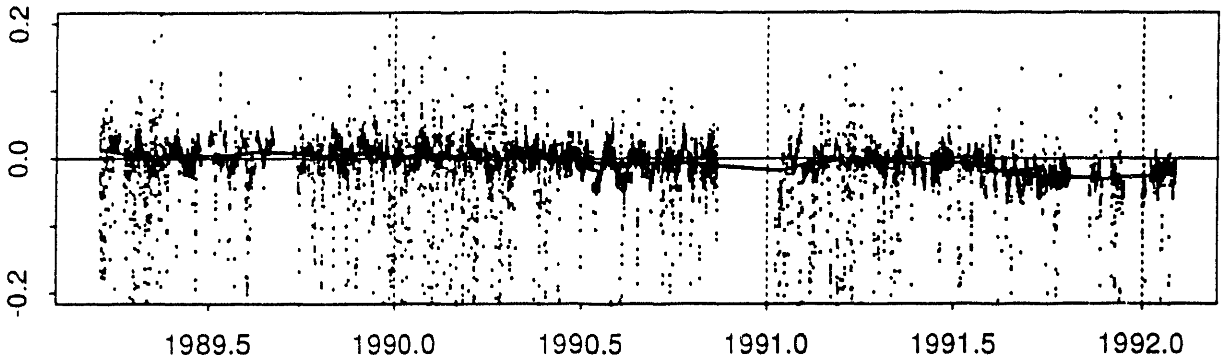

Fig. 9. Net clearness as a function of time at Kramer Junction, CA

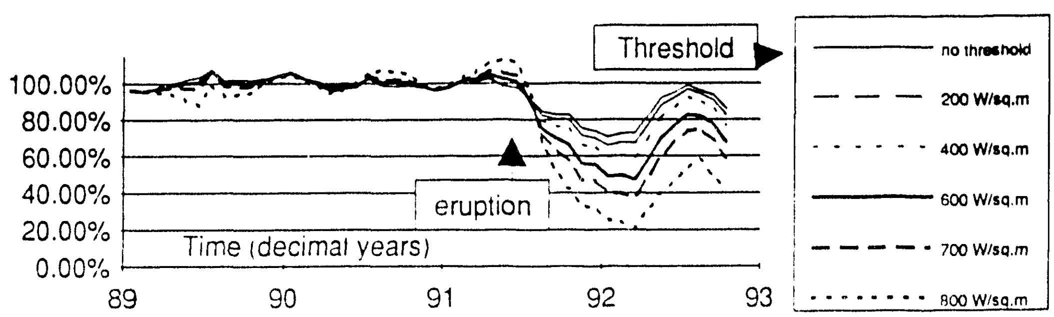

Fig. 10. Direct beam energy available above selected thresholds in Las Cruces, NM

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