CHANGES IN METEOROLOGICAL VARIABLES IN CORONEL OVIEDO, PARAGUAY, DURING THE TOTAL SOLAR ECLIPSE OF 3 NOVEMBER 1994

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Abstract. Solar global radiation, air temperature, relative humidity, and wind speed were measured in Coronel Oviedo, Paraguay, within the path of totality of the eclipse of 3 November 1994. Global radiation decreased gradually as the sun was being eclipsed and became negligible during the totality, then increased to their normal values. Surface air temperature decreased significantly, about 3 °C, with the lowest value occurring about 7 minutes after totality. Relative humidity, because of its dependence on temperature, increased as a consequence of the temperature decrease. Surface wind speed decreased gradually during the eclipse, as a result of the cooling and stabilization of the atmosphere. Although atmospheric pressure was also measured, it was not possible to record pressure changes clearly associated to the eclipse, since the pressure sensor was only able to detect pressure variations of at least 1 hPa.

Key words: solar eclipse, meteorology

1. Introduction

Changes in solar irradiance, air temperature, relative humidity, and wind, as well as in other geophysical variables, caused by a total solar eclipse are not quite the same as those occurring during the transition from day to night, because during the diurnal changes the variation of the solar elevation angle is large and gradual (Fernández *et al.*, 1993a, 1993b; Brenes *et al.*, 1993). During an eclipse, the sun is hidden by the moon in a few minutes, therefore its elevation angle does not change much.

On 3 November 1994 a total solar eclipse took place. The central eclipse began over the Pacific Ocean at 7°53.7′ S and 96°54.7′W, crossed the ocean and advanced eastward through South America (southern Peru and northern Chile, Bolivia, northern Argentina, Paraguay, and Brazil), crossed the Atlantic Ocean and ended at 31°58.5′ S and 46°45.2′ E (South of Africa). The elements and circumstances of the eclipse may be found elsewhere (e.g. Nautical Almanac, 1994; Espenak, 1987).

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This occasion provided a good opportunity to measure the changes in meteorological variables in Paraguay and compare them with other similar observations carried out in Costa Rica during the total solar eclipse of 11 July 1991 (Fernández *et al.*, 1993a, 1993b). In addition, the observations complement each other, since in Costa Rica the eclipse of 1991 occurred in the afternoon and in Paraguay the eclipse of 1994 occurred in the morning.

2. Instruments and the Observation Site

An automatic weather station was installed near the city of Coronel Oviedo in Paraguay at the 'Instituto Agropecuario Salesiano Carlos Pfannel' (25.27° S, 56.22° O, altitude: 163 m). The observation site was within the path of totality and very close to the central line of totality.

The surface variables recorded were: global radiation, air temperature, relative humidity, wind speed, and atmospheric pressure. The values used in the analysis are for every minute and they are the averages of values taken every 10 seconds. The data were stored in a data logger and transferred to a computer for their processing.

During the observation period the sky was completely clear (free of clouds). The observation site and its surroundings are flat land as is most of Paraguay.

At Coronel Oviedo, the totality lasted 3 min 26 s. The first, second, third, and fourth contacts occurred at 8 hr 33 min 40 s, 9 hr 42 min 57 s, 9 hr 46 min 13 s, and 11 hr 04 min 26 s, respectively.

3. Results

3.1. Global Radiation

Figure 1 shows the change in solar global radiation intensity over the observation site. Since the sky was completely clear (free of clouds) the curve is very smooth. The normal increase in global radiation during the morning was interrupted by the eclipse. The intensity decreased progressively as the sun was being eclipsed, and became negligible during totality, after which it increased to reach its normal course.

3.2. Air Temperature and Relative Humidity

Figure 2 shows the changes of air temperature and relative humidity with time. The temperature decreased about 3 °C (from the start up to totality). The lowest temperature did not occur during totality, but about 7 min later. This time lag was due to thermal inertia of the air and the ground.

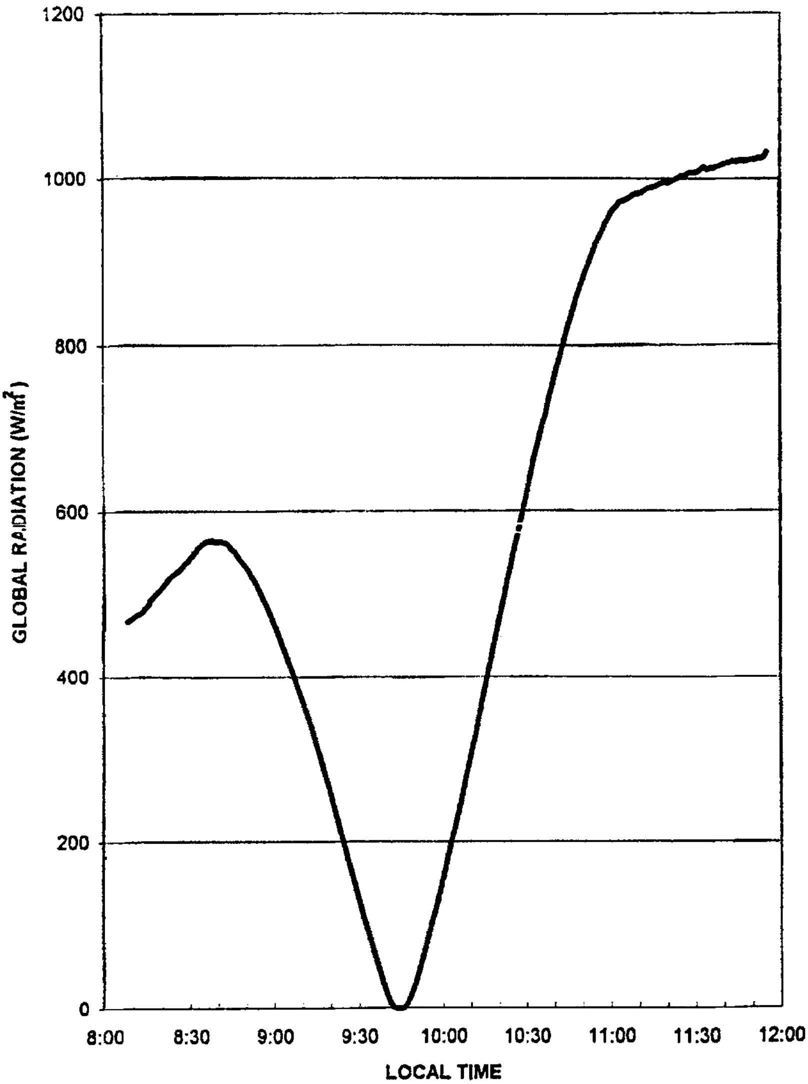

Figure 1. Temporal variation of global radiation in Coronel Oviedo, Paraguay, on 3 November 1994.

The rate of temperature decrease before totality was smaller than the rate of increase after totality, as the decrease was partly counteracted by the normal temperature increase that takes place in the morning. This contrast with the case studied by Fernández *et al.* (1993a), which took place in the afternoon.

In the normal cycle, air temperature increases faster during the morning than it decreases in the afternoon, because in the morning the heat flux downward to the soil and the heat dissipated by evaporation are small and most of the incoming energy from the sun is used to heat the air. In the afternoon, heat flux from the ground reduces the temperature decrease rate (Fernández *et al.*, 1993a).

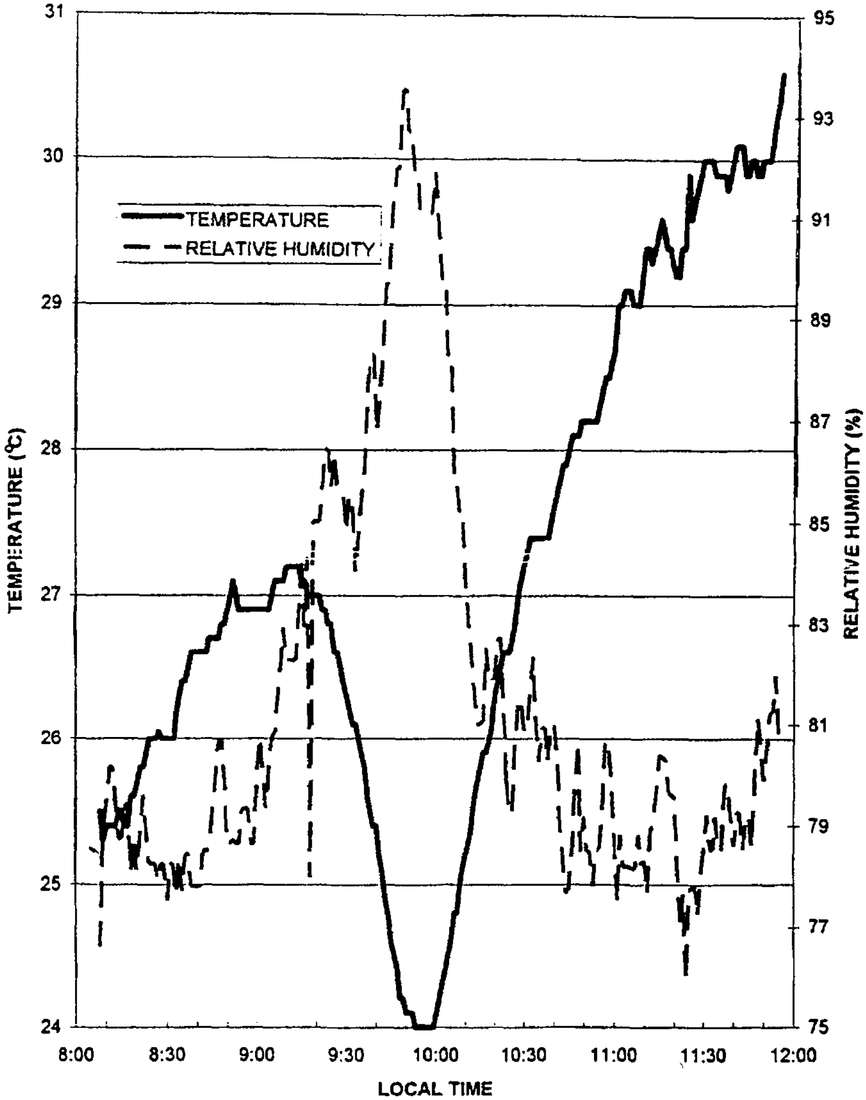

Figure 2. Temporal variation of temperature and relative humidity in Coronel Oviedo, Paraguay, on 3 November 1994.

Relative humidity, because of its dependence on temperature, increased as a consequence of the temperature decrease, as shown in Figure 3.

3.3. Wind speed

The wind speed decreased as the eclipse progressed toward totality, after which it increased to its normal values (Figure 3). Although wind direction was not recorded it was observed that it did not change significantly during the eclipse. A decrease

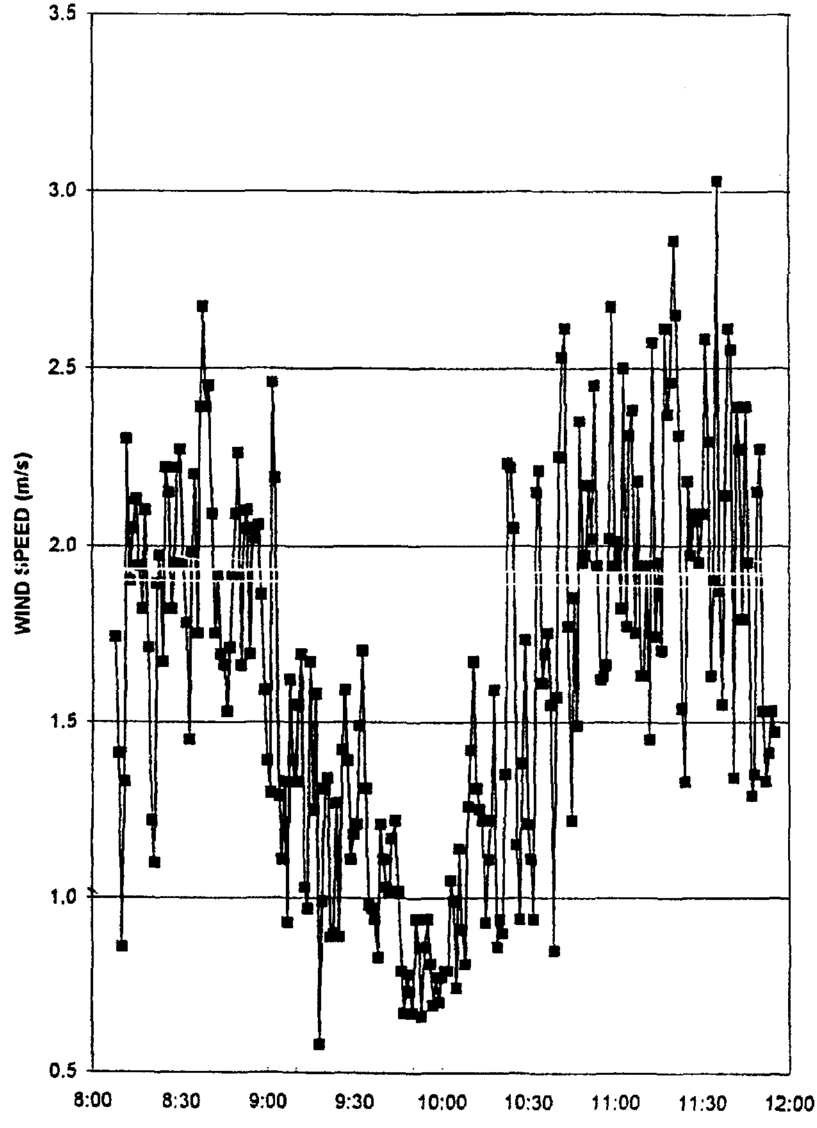

Figure 3. Temporal variation of wind speed in Coronel Oviedo, Paraguay, on 3 November 1994.

in wind speed during solar eclipses has been reported by several researchers (e.g., Clayton, 1901; Klein and Robinson, 1952; Anderson and Keefer, 1975; Fernández *et al.*, 1993a), being of particular interest the work of Fernández *et al.* (1993a). Antonia *et al.* (1979) found that even during a partial solar eclipse of about 80% totality the surface layer turbulence approximately follows a continuum of equilibrium states in response to stability changes brought about by the change in surface heat flux.

Fernández *et al.* (1993a) suggested as a possible explanation for the decrease in wind speed observed in Costa Rica during the total solar eclipse of 11 July 1991 that the thermal gradient, in the mesoscale and synoptic scale, decreased (due to the decrease in temperature) and, consequently, the wind speed did so, although with some time delay because of air inertia. They suggested such an explanation because in their case study, which occurred in early afternoon, Costa Rica was almost within the eclipse's umbra and the adjacent ocean on both sides of the country were just outside the path of totality. However, the observations in Coronel Oviedo, Paraguay, indicate that this is not the main reason for the decrease in wind speed. The explanation should be related to the gradual stabilization of the atmosphere as the temperature decreases, similar to what occur at sunset. So, the cooling and stabilization of the atmosphere is what produces the decrease in wind speed, being the full process similar to what is observed during the diurnal variation of the wind.

Diurnal variations of near-surface wind speed at different locations (e.g., Crawrord and Hudson, 1973; Mahrt, 1981), averaged over relatively long periods of time, show that wind speed increases sharply after sunrise, attains its maximum value in early afternoon, and decreases sharply until near sunset, after which a sudden decrease in the gustiness of the surface wind is observed. During the night time the wind speed changes very little. The ground adjust faster than the air above it to a sudden change in solar energy flux (radiative heating or cooling). Because of this, when surface cooling takes place an internal thermal layer (Townsend, 1976) propagates away from the ground through the surface layer (Antonia et al., 1979). As pointed out by Antonia et al. (1979), 'Townsend (1976) describes a tendency to deceleration of the mean flow with, as a most dramatic consequence, the collapse of the turbulent motion of the mean flow when the Richardson number exceeds a critical value'. The increase in surface wind speed following the morning inversion breakup is due to a more rapid and efficient transfer of momentum from aloft through the evolving unstable or convective planetary boundary layer (PBL) in the daytime (e.g., Arya, 1988).

Nevertheless, Jones (1976) found that during the 30 June 1973 solar eclipse the beginning of the decrease in wind speed occurred at the time when the vertical temperature gradient was still strongly adiabatic. Because of this, they pointed out that in this case it seems unlikely that the decrease in surface wind speed was due to an increase in hydrodynamic stability caused by a reduction in the magnitude of the temperature gradient such as occurs at sunset.

In Coronel Oviedo, the lowest value in wind speed was recorded about 3 minutes after the occurrence of the lowest temperature and about 10 minutes after totality. This is illustrated in Figure 4, which shows the changes in global radiation, temperature and wind speed. This figure may be compared with a similar one corresponding to the changes observed in Filadelfia, Costa Rica, during the total solar eclipse of 11 July 1991 (see Figure 8 of Fernández *et al.*, 1993a). In Filadelfia, Costa Rica, the lowest temperature occurred about 10 min after totality and the

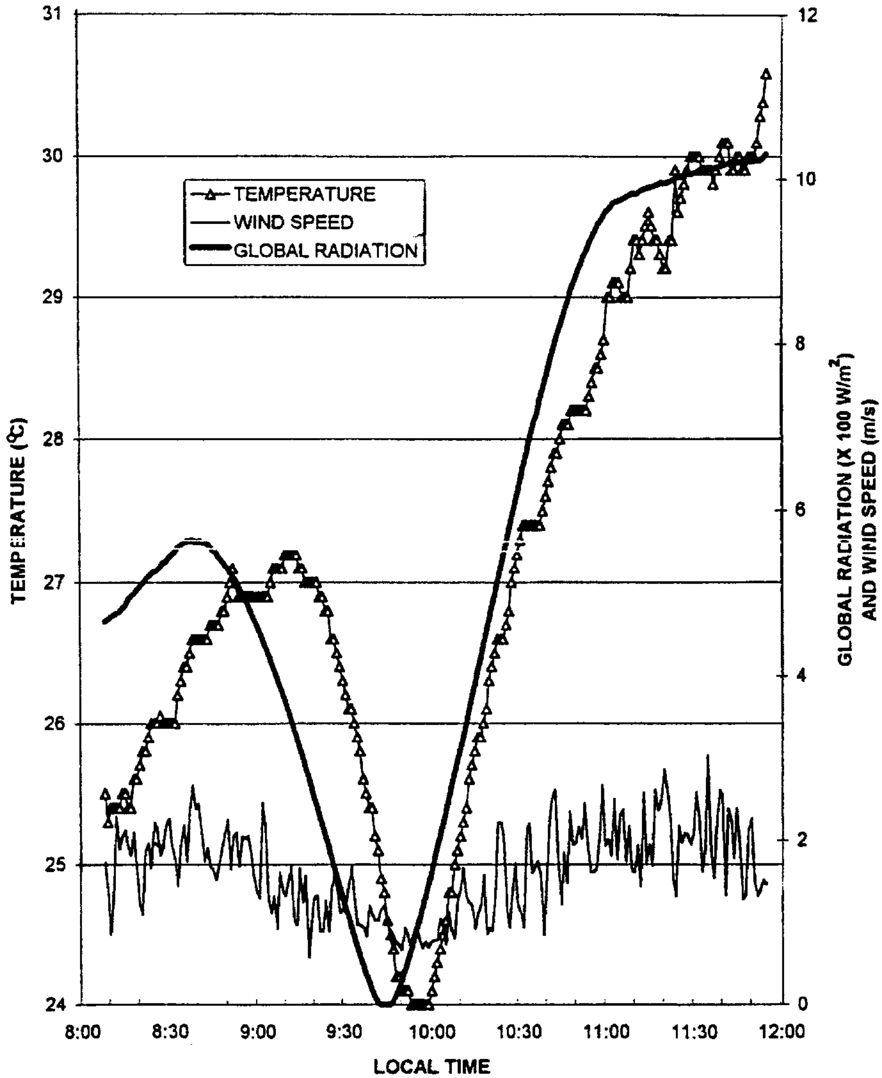

Figure 4. Temporal variation of global radiation, temperature, and wind speed in Coronel Oviedo, Paraguay, on 3 November 1994.

lowest value in wind speed was recorded about 15 min after the occurrence of the lowest temperature. It has been observed that this time lag depends on the locality (Fernández *et al.*, 1993a).

Although observations of wind speed were made only near-surface, it is expected that above the surface layer during the eclipse the wind speed behaves similar to that during the diurnal cycle. In the latter case, the diurnal wave above the surface layer becomes about 180° out of phase with respect to surface wind (the minimum value in wind speed occurs around noon) and the amplitude of the wave increases with height up to about the middle of the convective PBL (e.g., Crawford and Hudson, 1973; Mahrt, 1981). Farther up, the amplitude of the diurnal variation of wind speed is expected to decrease and vanish at the maximum height of the daytime PBL (Arya, 1988).

3.4. Atmospheric Pressure

It was not possible to record changes in atmospheric pressure clearly associated to the eclipse, since the pressure sensor was only able to detect pressure variations of at least 1 hPa. The atmospheric pressure was 993 hPa from 08:08 to 11:43 hours (local time) with a few exceptions. During the partial phase before totality, some sporadic values of 994 hPa were recorded. After 11:47 hours (after the eclipse had ended), some values of 992 hPa were recorded.

Chimonas and Hines (1970) suggested that the cooling action of the eclipse – the cold shadow of the moon moving at a supersonic speed through the atmosphere – generates internal gravity waves. They estimated a maximum pressure perturbation, at a distance of 10,000 km from the shadow, of 10^{-5} atmosphere at the surface and of 10^{-1} of ambient pressure at 200 km altitude. In this 'bow-wave model' of Chimonas and Hines (1970), also treated in Chimonas (1970) and Chimonas and Hines (1971), the source of the gravity waves is the cooling of the ozone layer. The magnitude as predicted by Chimonas (1970) was of about 0.2 Pa at the centerline with the value increasing with distance from the centerline. Chimonas (1973) proposed the 'Lamb edge-wave model', in which the source of the waves is the cooling of water vapor in the troposphere. Both models predict propagation velocities at approximately the local sound speed. The predicted magnitude of gravity waves at ground level is at least a factor of 10 below ongoing pressure fluctuations of comparable period, while Lamb waves could be an order of magnitude or more greater in size than gravity waves (Jones, 1976). Observations of ionospheric disturbances during total solar eclipses (e.g., Davis and da Rosa, 1970; Schodel *et al.*, 1973; Beckman and Clucas, 1973; Jones and Bogart, 1975; Bertin *et al.*, 1977) suggest a possible confirmation of what was proposed by Chimonas and Hines (1970).

Several atmospheric pressure ground-based measurements during solar eclipses (e.g., Upton and Rotch, 1887, 1893; Kimball and Fergusson, 1919; Lindholm and Bergstein, 1923; Anderon *et al.*, 1972; Jones *et al.*, 1992) show pressure changes between 20 and 30 Pa. Clayton (1901) and Klein and Robinson (1952) found approximate pressure changes of 10 and 45 Pa, respectively, while Jones (1976) applying cross-correlation analysis found a preliminary upper limit of 17 Pa being placed on the magnitude of the waves. In another experiment during the total solar eclipse of 23 October 1976, Goodwin and Hobson (1978) found the internal gravity waves to have a peak-to-peak amplitude of 0.1 to 0.2 Pa, a period of 23 min and a velocity of 310 m s^{-1}. McIntosh and ReVelle (1984) detected traveling pressure waves associated to the solar eclipse of 26 February 1979 with a velocity of 10 m $^{-1}$; the wave period and amplitude were approximately 120 s and 12 Pa, respectively;

the duration of the wave train was approximately 3 hr. Since it is clear that the waves observed by McIntosh and ReVelle are not related to the predictions of either the 'bow-wave model' (Chimonas and Hines, 1970, 1971; Chimonas, 1970) and the 'Lamb edge-wave model' (Chimonas, 1973), they suggested a source mechanism similar to the low level nocturnal jet. Jones *et al.* (1992) observed in the southeast of the United Kingdom a 30 Pa rise and fall in surface atmospheric pressure over a period of about 2 hr, which could have been related to the total solar eclipse of 22 July 1990. The corresponding wave speeds were between about 44 and 230 m s^{-1}. In this case, Jones *et al.* ruled out the possibility of internal gravity waves resulting from the cooling of the ozone layer, because they should have been too weak to detect. They pointed out the possibility of Lamb waves (external gravity waves) caused by the cooling of the lower troposphere (Chimonas, 1973), although such waves travel at the local speed of sound, faster than the speeds calculated by Jones *et al.* They also considered the possibility of a solitary wave (Ramamurthy *et al.*, 1990), though for an eclipse origin the required speeds are somewhat large. Other explanations for their observations could be associated with a variety of normal weather related phenomena.

4. Conclusions

The total solar eclipse of 3 November 1994 brought the opportunity of studying changes in meteorological variables and compare them with other similar observations.

Even thought the decreases in solar irradiance and temperature were obvious, it was interesting to quantify them. Global radiation decreased as the eclipse progressed toward totality, after which it increased again to reach normal values. Temperature also decreased but its lowest value was recorded about 10 min after totality. Relative humidity, because of its dependence on temperature, increased as a consequence of the temperature decrease. The wind speed decreased gradually as the eclipse progressed toward totality. This was due to the cooling and stabilization of the atmosphere. Because of limitations in the sensitivity of the pressure sensor, it was not possible to observe changes in atmospheric pressure associated to the eclipse.

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