AIR TEMPERATURE AND WIND CHANGES IN COSTA RICA DURING THE TOTAL SOLAR ECLIPSE OF JULY 11, 1991

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Abstract. Air temperature and wind measurements on the surface and in the free atmosphere taken during the total solar eclipse of July 11, 1991, are analyzed. Surface air temperature decreased significantly, 2 to 5 °C in general, with the lowest values occurring 10 to 30 minutes after totality. In some places, surface wind speed decreased gradually during the eclipse, as a result of the decrease of air temperature and temperature gradients. In other places, it increased due to local atmospheric conditions. A radiosonde launched at 13:26 LT (local time) appeared to have been affected by the moon's shadow at about 13 km height. At this altitude temperature was relatively lower than usual and the balloon carrying the radiosonde experienced an upward acceleration. Also at this altitude wind direction changed and wind speed decreased

1. Introduction

Changes in solar irradiance, temperature, wind and other 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. During an eclipse, the sun is hidden by the moon in a few minutes, therefore its elevation angle does not change much.

Fernández *et al.* (1993) analyzed and discussed the changes in solar irradiance observed in Costa Rica during the total eclipse of July 11, 1991. In this article, surface air temperature and wind speed are analyzed, as well as some observations taken in the free atmosphere up to an altitude of about 15 km.

2. Instruments and Observation Sites

Figure 1 and Table I show the observation sites and the instruments used in surface observations, respectively. The sites were chosen along the path of the eclipse and they do not represent all the stations that recorded temperature and wind speed. For upper air observations, type GMD radiosondes were launched at Juan Santamaría International Airport, Alajuela, located at 10° N, 84°12′ W, and 920 m above sea level (number 7 in Figure 1).

The general characteristics of the eclipse are described in Fernández *et al.* (1992). Over Costa Rica, along the central line of the umbra, the totality had an average duration of 5.5 min. In Peñas Blancas (northern border) the first contact occurred by 12:40 LT (local time) and the beginning of totality by 14:01 LT. In Paso Canoas (southern border) the first contact occurred by 12:50 LT (about

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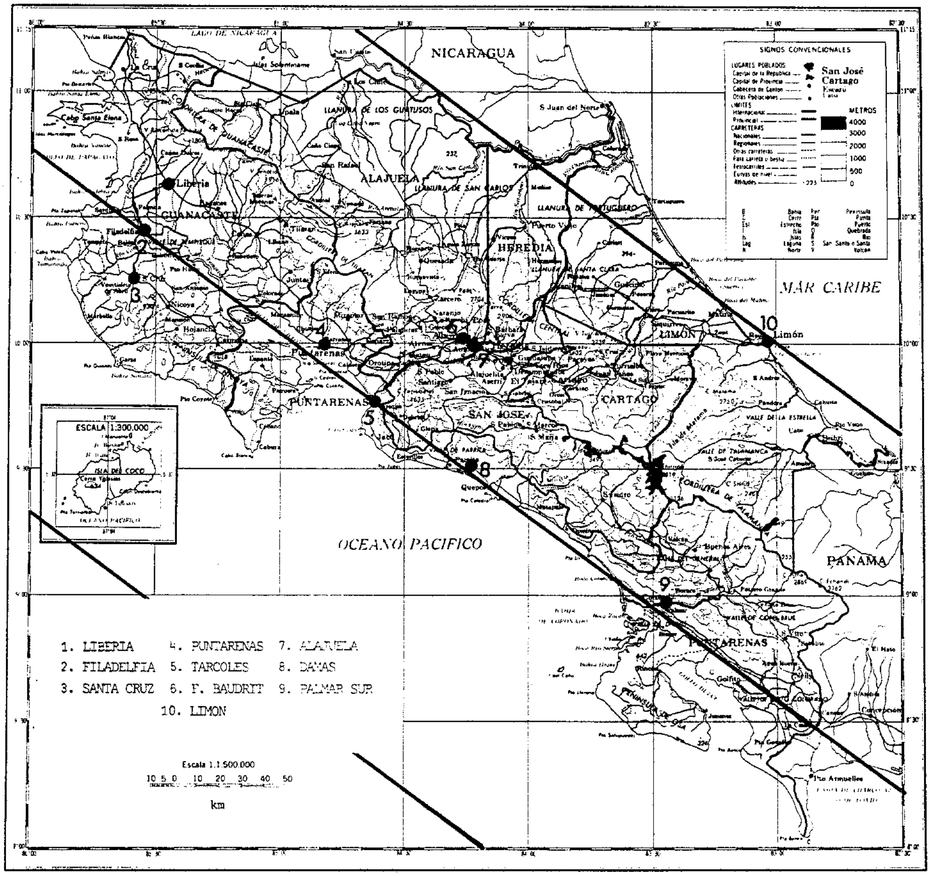

Fig. 1. Map of Costa Rica showing the sites where the measurements were taken. The two external lines were the borders of the path of totality and the middle line was the central line of totality.

10 min later than in Peñas Blancas) and the beginning of totality near 14:09 LT. Last contact was near 15:17 LT in Peñas Blancas and 15:23 LT in Paso Canoas. Similar information for other localities can be found in a number of publications (e.g., Fernández *et al.*, 1992).

3. Surface Temperature Changes

Figures 2, 3 and 4 show the change of air temperature with time in the sites indicated in Figure 1. The change was significant in all sites. In Santa Cruz and Filadelfia the temperature decreased between 2 and 2.5 °C, in Puntarenas 2.7 °C, in Liberia, Alajuela (Juan Santemaría International Airport), and Palmar Sur between 3 and 3.5 °C; in Damas 4.7 °C, and in the Fabio Baudrit Experimental Station 5.5 °C. The largest change registered, 8.5 °C, occurred in Tárcoles, influ-

TABLE I

Instruments used for surface measurements

Station No.	Station	Temperature	Wind
1	Liberia	Daily hygrothermograph (Wilh. Lambreich)	Daily anemocinemograph (Fuess)
2	Filadelfia	Thermistor. (Omnidata automatic weather station)	Vaisala sensor. (Omnidata automatic weather station)
3	Santa Cruz	Mercury thermometer	Woelfle anemograph
4	Puntarenas	Thermistor. (Omnidata automatic weather station)	Daily anemocinemograph (Fuess)
5	Tárcoles	Thermistor	–
6	Fabio Baudrit	Thermistor	Universal anemocinemograph
7	Alajuela (Airport)	Vaisala automatic weather station	–
8	Damas	Daily hygrothermograph (Wilh.Lambreich)	Woelfle anemograph
9	Palmar Sur	Daily hygrothermograph (Wilh. Lambreich)	Universal anemocinemograph
10	Limón	Daily hygrothermograph (Wilh. Lambreich)	Fuess anemocinemograph

enced by the proximity of a severe thunderstorm that reached the area shortly after totality. Even in Limón, where totality lasted only seconds, there was a decrease of 3 °C.

Lowest temperatures did not occur during totality, but about 10 to 30 min later, depending on the locality. This time lag was due to the thermal inertia of the air and the ground. A similar time lag is usual on clear days, as shown schematically in Figure 5. The diurnal maximum does not occur when the sun is in the zenith, but some time after which may be of several hours depending on the circumstances. The explanation (e.g., Lowry, 1969; Geiger, 1965) is that at noon and some time after, energy comes at a faster rate than it is dissipated, therefore air temperature increases, up to the moment when rates become equal.

The rate of temperature decrease before totality was in general larger than the rate of increase after totality, as the increase was partly counteracted by the normal temperature decrease that takes place after 14:00 LT.

In the normal diurnal 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.

The eclipse took place several minutes later in the southern part than in the northern part of the country. The starting time of the temperature descent reflected

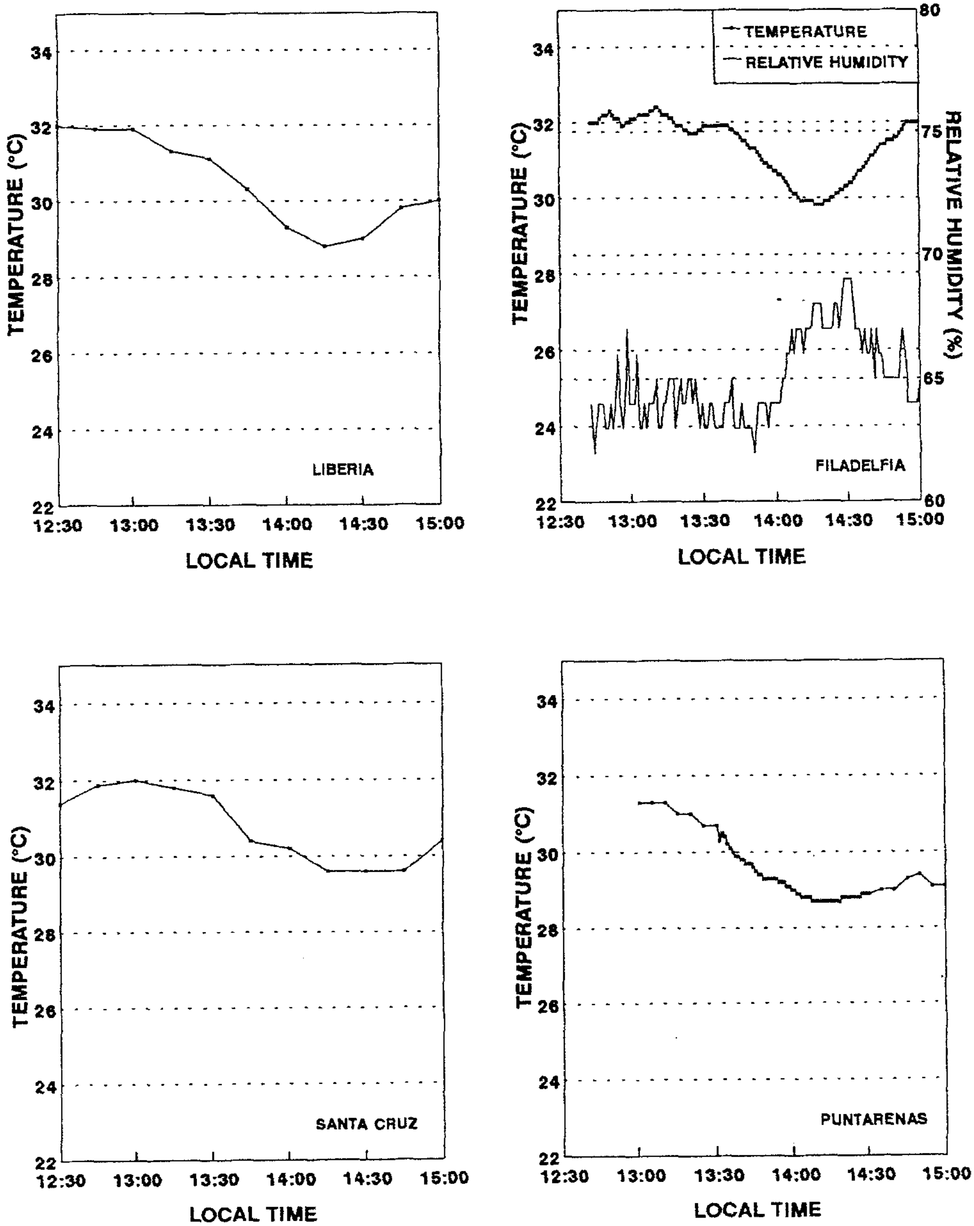

Fig. 2. Temporal variation of temperature on July 11, 1991, in Liberia, Filadelfia, Santa Cruz, and Puntarenas. For Filadelfia, the variation in relative humidity is also shown.

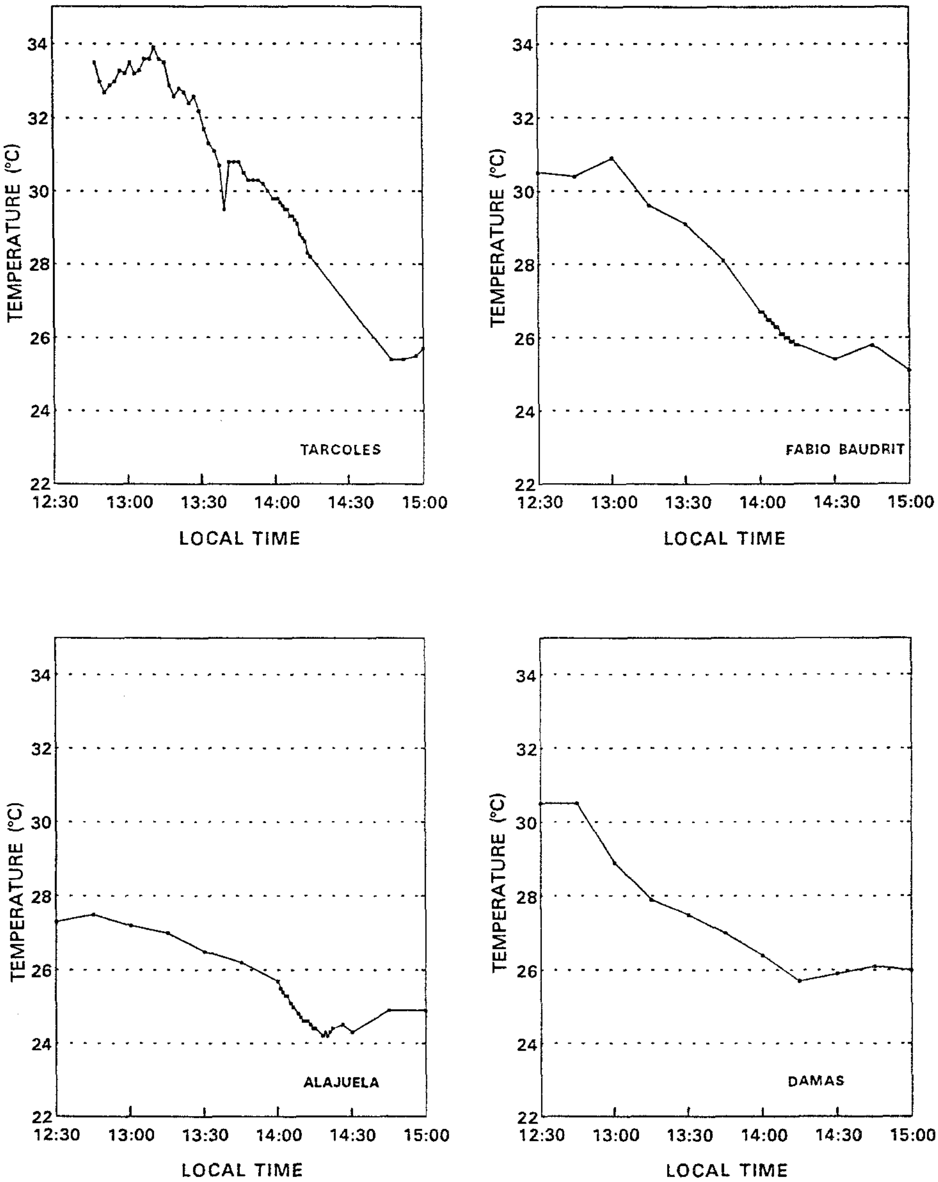

Fig. 3. Temporal variation of temperature on July 11, 1991, in Tárcoles, Fabio Baudrit, Alajuela, and Damas.

this time delay, as can be seen by comparing Palmar Sur in the south (Figure 4) with Liberia in the north (Figure 2).

Even if the temperature decrease did not exceed 5 °C, the sudden change in temperature made people experience a sensation of "cold", corresponding to a larger temperature change. When the body is heated by the sun and the air is

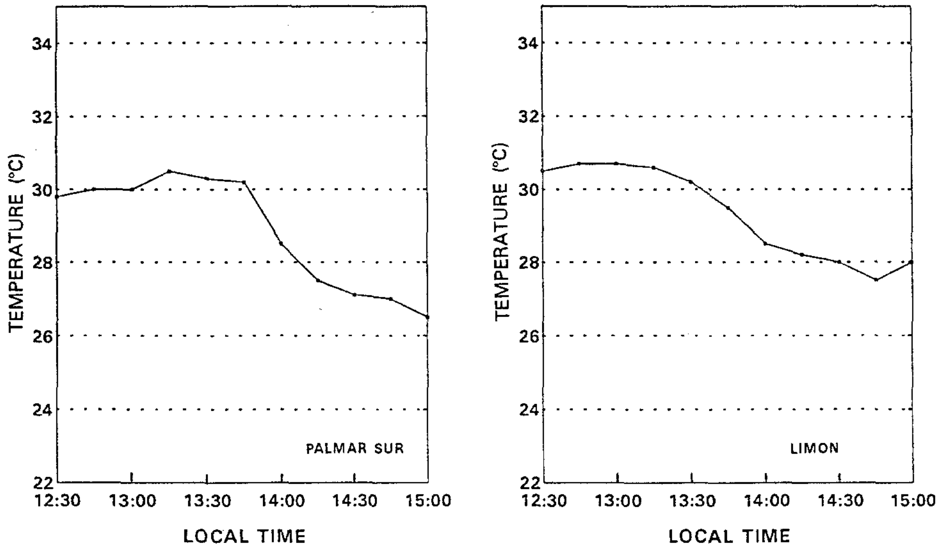

Fig. 4. Temporal variation of temperature on July 11, 1991, in Palmar Sur and Limón.

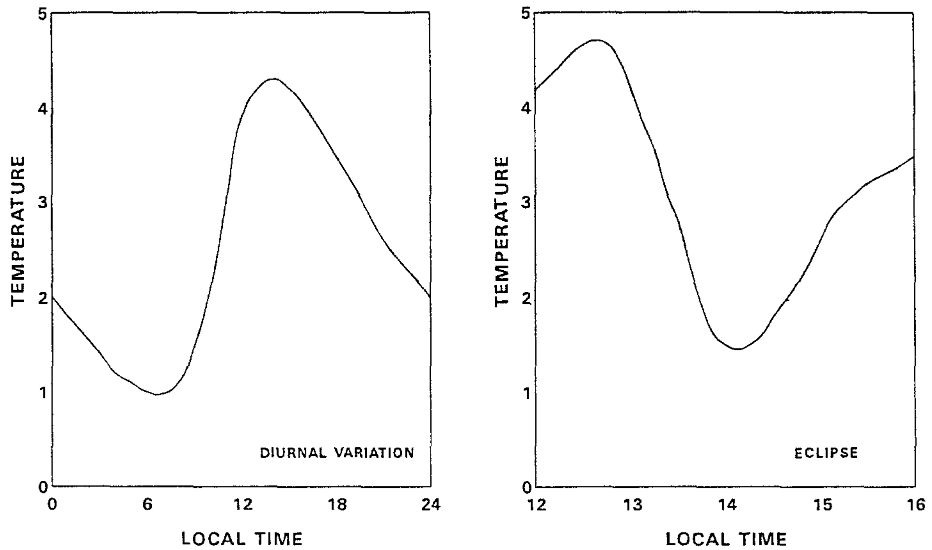

Fig. 5. Schematic representation of: (a) the diurnal variation of temperature, and (b) the variation of temperature during a total solar eclipse.

warm, the internal production of heat by metabolism is low, the transpiration is intense and the body irradiates energy. With the sudden elimination of energy from the sun during the eclipse, in addition to the decrease of air temperature, the reaction of the body is not immediate: the metabolism continues to be low and the skin continues to irradiate and transpire profusely. For a short time, more energy is being lost than received; the body is cooled and the reaction is the chill, unconscious reaction which informs the nervous system that the thermal conditions have changed, and therefore the metabolism and the transpiration should diminish.

Regarding air humidity, there were no significant changes in absolute humidity. Relative humidity, because of its dependence on temperature, increased as a consequence of the temperature decrease, as shown in Figure 2 for Liberia.

4. Changes in Surface Wind

Figures 6 and 7 show the changes in wind speed recorded at several sites (whose locations are indicated in Figure 1).

With the exception of Filadelfia, where the values were taken every minute with an automatic weather station, the values were calculated from the wind run recordings in the period prior to the time at which the values are plotted in the figures.

In Liberia, Filadelfia, and Santa Cruz – localities without major orographic effects and where the predominant wind was the trade wind from the northeast, with direction almost perpendicular to the eclipse's path – the wind speed decreased, without any significant change in wind direction, as the eclipse progressed toward totality. A possible explanation is 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.

In Santa Cruz and Filadelfia, the lowest values in wind speed were recorded between 10 and 15 min after the occurrence of the lowest temperatures, and between 20 and 25 min after totality. This is illustrated in Figure 8, which shows the changes in global radiation, temperature, and wind speed in Filadelfia.

The time lag of the decrease in wind speed with respect to the decrease in temperature was not observed at Liberia. At this station, the wind speed decreased, in general, until about 13:45 LT and increased afterward (Figure 6). The increase between 13:45 and 14:30 LT, where a decrease would be expected as a result of the eclipse, could have been caused by deep convection that occurred during that period on the slopes of a mountain range to the east-northeast of the meteorological station.

In Puntarenas (Figure 6), a slight decrease in wind speed was observed during the partial phase of the eclipse (between 13:15 and 13:45 LT). At 14:08 LT a storm (cumulonimbus) invaded the area and caused the increase in wind speed

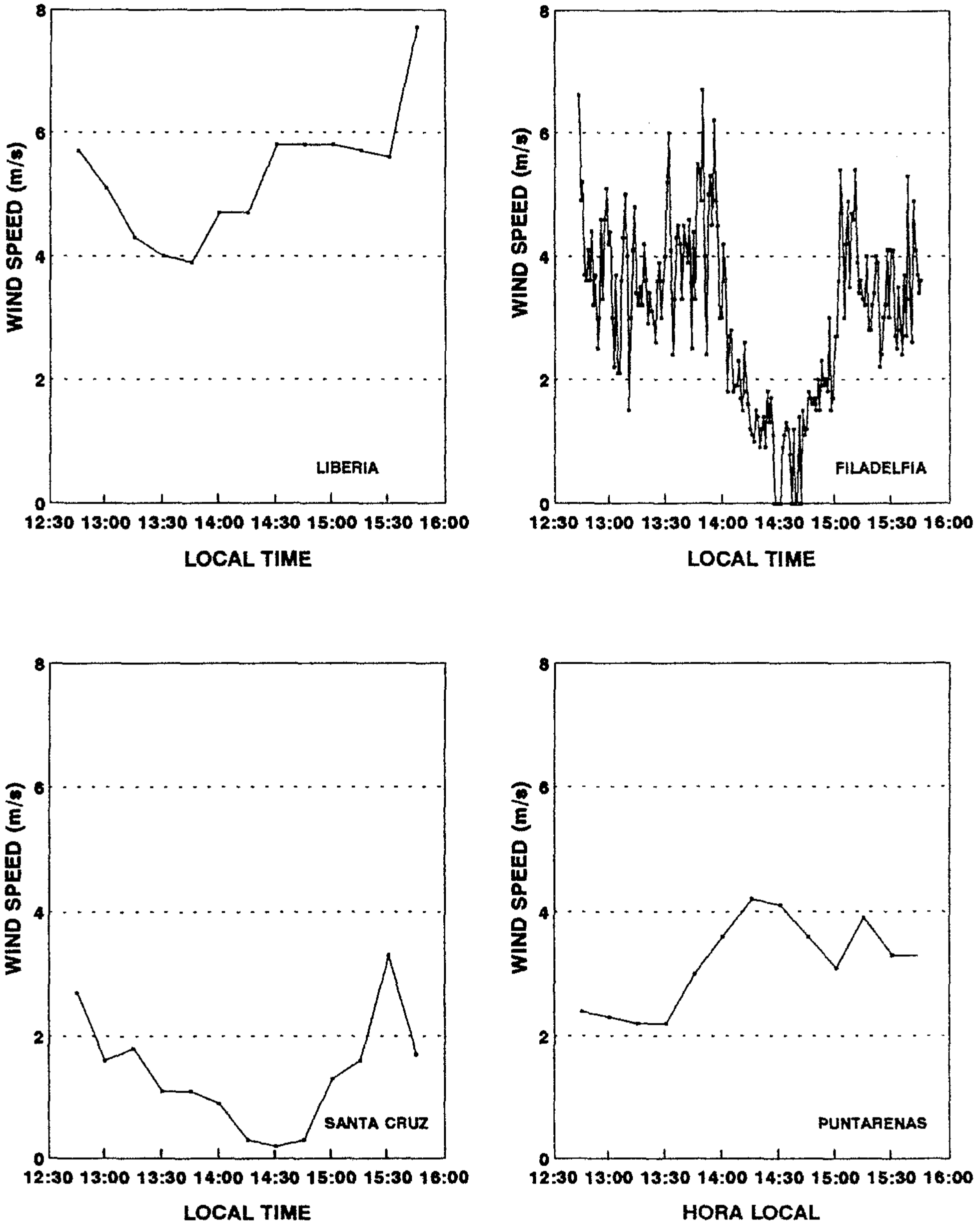

Fig. 6. Temporal variation of wind speed on July 11, 1991, in Liberia, Filadelfia, Santa Cruz, and Puntarenas.

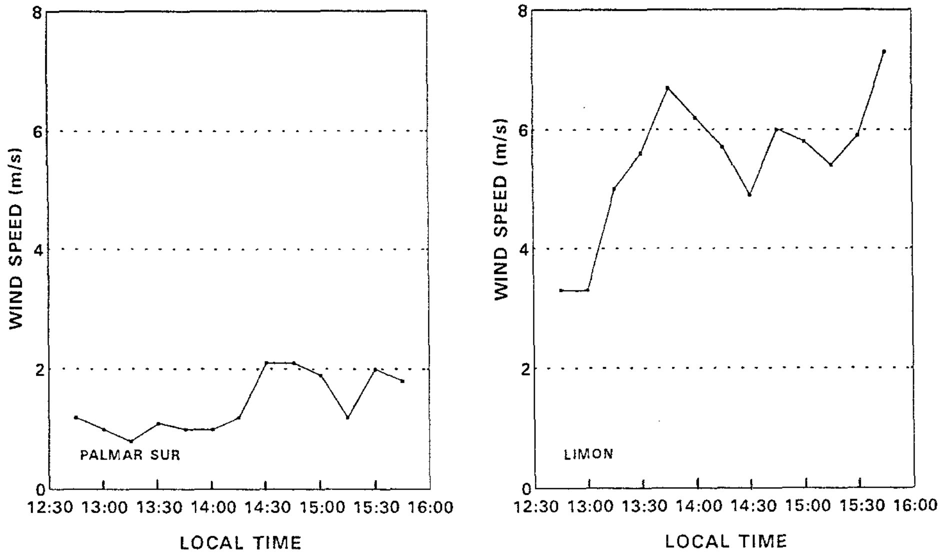

Fig. 7. Temporal variation of wind speed on July 11, 1991, in Palmar Sur and Limón.

(the wind direction changed slightly from west-southwest to south-southwest). The storm, which was neither strong nor continuous, lasted until about 18:00 LT.

In Palmar Sur (Figure 7), the wind speed before the eclipse was very small. The increase that started at 14:15 LT was produced by convective clouds. The decrease near 15:15 LT was possibly a result of local atmospheric conditions and not the eclipse. The subsequent increase may have been caused by the effects of convection; a storm was observed near 15:40 LT to the northwest of the meteorological station. During the day, significant changes in wind direction were observed, but between 13:15 and 15:15 LT, approximately, the wind blew from the south.

In Limón (Figure 7), where the wind direction during the eclipse was from the north-northeast, the wind speed increased during the partial phase before totality, and some time after it, due to local atmospheric conditions (there was convective activity and the sky was completely cloudy). The relative decrease recorded near 14:30 LT could have been caused by the eclipse, together with local atmospheric effects. Near 16:00 LT, a thunderstorm occurred over the meteorological station (a few minutes before a wind gust of 11.6 m/s was recorded), which explains the increase in wind speed just before that time.

From the previous discussion, it may be concluded that the effect of the eclipse on the wind was to produce a decrease in speed as the phenomenon progressed toward totality. As mentioned, this may have been caused by the decrease in temperature in the shadow's area and, consequently, of the thermal gradient. Where such a decrease in wind speed was not observed, it was because the effects of local atmospheric conditions predominated over the effect of the eclipse.

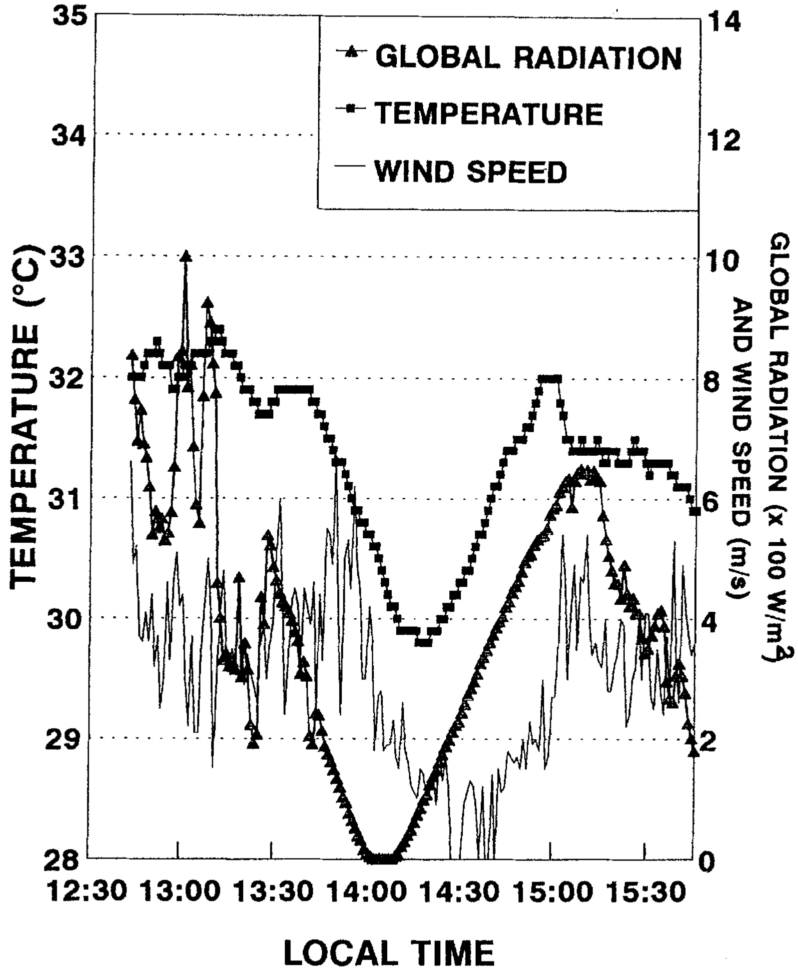

Fig. 8. Temporal variation of global radiation, temperature, and wind speed in Filadelfia, Guanacaste, on July 11, 1991.

5. Observations in the Free Atmosphere

Measurements of pressure, temperature, humidity, and wind from the surface up to about 15 km were taken at Juan Santemaría International Airport, Alajuela (number 7 in Figure 1).

Two soundings were taken on the day of the eclipse; one at 06:00 LT (12:00 GMT), which is taken every day, and the other at 13:26 LT. For comparison purposes another sounding was taken on July 16, 1991, at 14:00 LT, under similar synoptic conditions to the day of the eclipse.

Although it had been planned to take a sounding at 12:30 LT and other just after totality, this was not possible; only one, at 13:26 LT, was made. The moon's

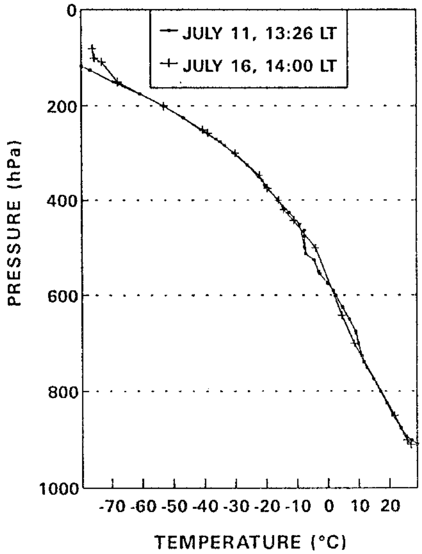

Fig. 9. Vertical variation of temperature at Juan Santamaría International Airport, Alajuela (10°00′ N, 84°12′ W), on July 11, 1991, at 13:26 LT (local time), and on July 16, 1991, at 14:00 LT.

shadow affected the balloon carrying the radiosonde at an altitude of about 13 km. The balloon's average speed of ascent is 5.4 m/s. When the balloon reached the 175 hPa level (approximately 13 km), its speed of ascent increased to 8.8 m/s, an increase of 63% of its average speed. From this observation, it can be inferred that the lower temperature in the shadow's region affected the balloon's buoyancy.

In principle it would be expected that during an eclipse the temperatures at different levels in the atmosphere would be lower than the monthly average values at approximately the same time of occurrence of the eclipse. As these average values are not available, in Figure 9 the sounding of July 11, 1991, at 13:26 LT is compared with the sounding of July 16, 1991, at 14:00 LT. Figure 10 shows the vertical variation of the temperature difference between the sounding of July 11, 1991, at 13:26 LT and the soundings of July 16, 1991, at 14:00 LT and July 11, 1991, at 06:00 LT. In addition, the vertical profiles of wind for these soundings are shown in Figure 11. Comparisons of this type have the limitation that the atmospheric conditions change from day to day and, therefore, the observed changes could be due to such variations and not to the eclipse. Nevertheless, some information can be inferred by taking into account that changes in temperature due to variations in solar energy are smaller at upper tropospheric levels than at lower levels, and that the upper troposphere and lower stratosphere are, in general, less affected by the synoptic conditions than the lower and middle tropospheric levels.

The fact that temperatures above the 175 hPa level were significantly lower on

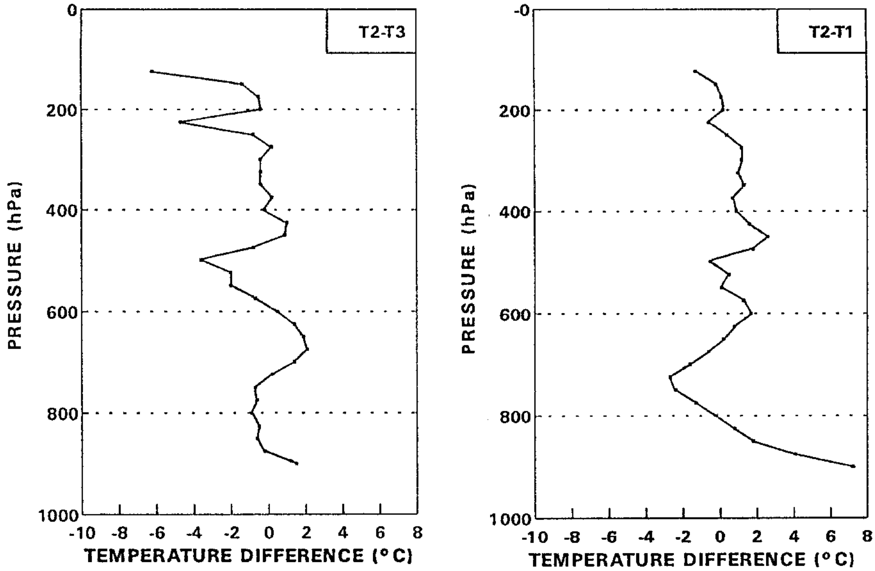

Fig. 10. Vertical variation of the temperature difference between the sounding of July 11, 1991, at 13:26 LT (T2), and the soundings of July 16, 1991, at 14:00 LT (T3), and of July 11, 1991, at 06:00 LT (T1). Positive values indicate that the temperatures for the sounding of July 11, 1991, at 13:26 LT, were higher and negative values indicate that they were lower.

July 11, 1991, at 13:26 LT than on July 16, 1991, at 14:00 LT (Figures 9 and 10), is consistent with the acceleration experimented by the balloon when it was affected by the moon's shadow at a similar level.

The temperature differences between the soundings of July 11, 1991, at 13:26 LT and 06:00 LT (Figure 10) suggest that although the temperatures decreased as the eclipse progressed toward totality, they were always higher than those recorded in the sounding taken at 06:00 LT, except for the decrease between 800 and 650 hPa (which possibly was due to the synoptic conditions) and above 175 hPa (caused by the moon's shadow).

The wind profile for the sounding of July 11, 1991, at 13:26 LT (Figure 11) shows that, near the 175 hPa level, a change in wind direction of about 45° occurred, and wind speed decreased from 5 m/s to near 1.5 m/s. These changes could have been caused by the movement of the moon's shadow. The westerly wind which was observed near 150 hPa may not have been associated with the eclipse, since it was also observed before and after the occurrence of the phenomenon (Figure 11).

It was not possible to take measurements of the upper atmosphere, since the appropriate equipment was not available to the authors. Nevertheless, such measurements have been taken in other eclipses. They are described below in order to complement our observations in Costa Rica.

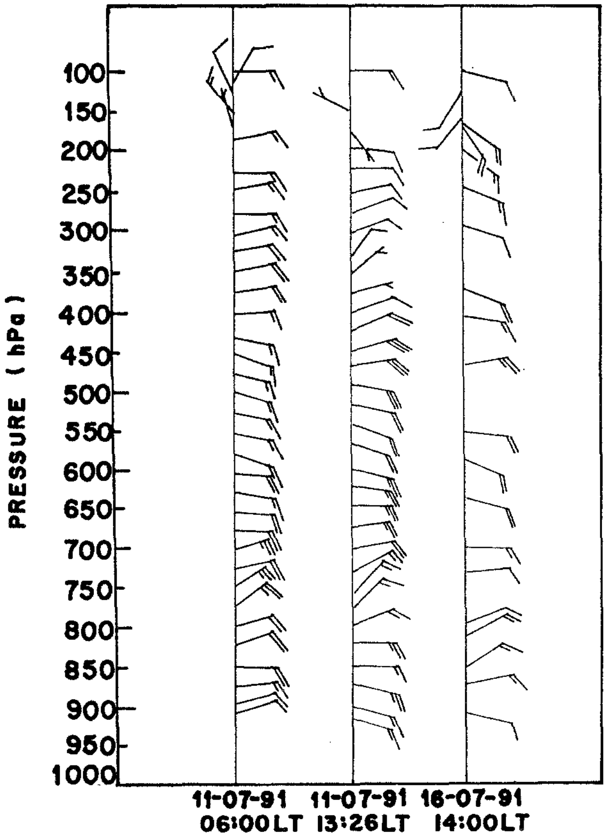

Fig. 11. Vertical profiles of wind on July 11, 1991, at 06:00 and 13:26 LT (local time), and on July 16, 1991, at 14:00 LT. A full bar (the longest) corresponds to 5 m/s, and the direction is from where the wind is blowing.

Several researchers have taken soundings, utilizing rockets, to determine temperature and wind perturbations between approximately 30 and 60 km. Ballard *et al.* (1969) made observations in Tartagal, Argentina, for the eclipse of November 12, 1966. The totality in Tartagal lasted 1 minute and 28 s and started at 10:33:51 LT; the eclipsed ended at 11:56:34 LT. The temperatures recorded the day before the eclipse at 06:00 and 15:00 LT were essentially the same as those recorded in the day of the eclipse at the same hours. Nevertheless, on the day of the eclipse the temperatures between 50 and 60 km decreased as the eclipse started and progressed toward totality, increasing afterward. During the eclipse the wind profiles showed a change in speed between 40 and 60 km.

Henry and Quiroz (1970) analyzed temperature data of an experiment carried out in Wallops Island, Virginia, for the total eclipse of March 7, 1970. The main characteristics found were: (1) a perturbation in the temperature field, within the period of the eclipse and mainly between 40 and 60 km; (2) a maximum amplitude of 5 to 7 °C between 45 and 55 km, with the lowest temperatures occurring a few minutes after totality; (3) a sudden heating just before the end of the eclipse, which could have been partially spurious.

A large variation of temperature, in a deep atmospheric layer, produces a large perturbation in the pressure field and, consequently, appreciably affects the circulation. 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} at the surface and of 10^{-1} at 200 km altitude. Davis and da Rosa (1970), analyzing data of the columnar content of electrons in the ionosphere, found a possible confirmation of what was suggested by Chimonas and Hines.

Meteorological rockets were also used to measured the ozone concentration at high altitudes in Tartagal, Argentina, during the eclipse of November 12, 1966 (Randhawa, 1968; Ballard *et al.*, 1969). When the sonde passed through the moon's shadow between 60 and 54 km, it recorded an ozone concentration greater (more than double) than the one recorded the previous day at the same time. In addition, when the sonde left the moon's shadow, a decrease in ozone concentration was recorded. Measurements of the total amount of ozone carried out at the surface during an eclipse (Stranz, 1961; Henry and Quiroz, 1970) also show an increase in ozone. This increase is caused by the reduction of chemical reactions during the eclipse and was deduced theoretically by Hunt (1965).

6. Conclusion

As in the case of solar irradiance (Fernández *et al.*, 1993), decrease in temperature as the eclipse progressed toward totality was inferred, and was interesting to quantify. This turned out to be in the 2–5 °C range for most of the stations. The lowest temperatures occurred between 10 and 30 min after totality.

As a consequence of the decrease in temperature, the wind decreased gradually as the eclipse progressed toward totality. Nevertheless, during the eclipse, an increase in wind speed was recorded at several sites. However, this was caused by local meteorological conditions.

A radiosonde was affected by the moon's shadow at an altitude of about 13 km (approximately the 175 hPa level), where the temperatures were relatively low. At this altitude, the balloon carrying the radiosonde was significantly accelerated, a change in wind direction occurred, as well as a decrease in wind speed.

Acknowledgments

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Damas, and Armando Soto at Fabio Baudrit Experimental Station. The data for Filadelfia were taken, installing an automatic weather station of ICE in the farm El Escarbadero, by Luis E. Acuña, Marco V. Alvarado, Rafael Enrique Chacón, and Porfirio Machado (all of ICE), and Jorge A. Amador (UCR). These data were kindly provided by the Department of Hydrology of ICE. Paulo Manso coordinated the measurements made at Juan Santamaría International Airport. Hugo Hidalgo-León helped with the figures.

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